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RADIO SECTION

THE LIFE OF OXIDE CATHODES IN MODERN RECEIVING VALVES

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SUMMARY

The paper attempts to integrate all information on oxide cathodes which may have a bearing on life span. Original research results are included in addition to published work from other sources.

Two broad problems are distinguished as prerequisites to effective control of valve quality from the aspect of longevity. First, production processes must be more clearly understood in order that they may be closely related to valve life, and secondly, a short-term method for assessment of valve life must be developed.

In considering a solution of the first problem, functional failure and cathode failure are recognized as the two main causes of valve faults. Only the latter is considered in detail, and this is subdivided into failures due to gas attack, to excessive interface feedback and to excessive evaporation of the activated cathode. Production processes (developed on a laboratory scale by the Post Office) which go far towards excluding gas attack are outlined, and valves have been produced which show no deterioration in total emission after 10 000 h of use. Interface feedback is identified with impurities in the core, and control of the impurity concentration may set a limit to the magnitude of the feedback. Cathode evaporation may be reduced to negligible amounts in gas-free valves by appropriate reduction of running temperature, which also achieves a considerable saving in heater power.

The efficacy of these attempts to avoid valve failure is judged by the short-term methods for assessing valve life, which are advanced as solutions of the second broad problem. These take the form of short life-tests making use of total-emission measurements and a.c. measurements of interface resistance. The more usual measurements of space-charge-limited mutual conductance are used in correlation of the newer tests.

(1) INTRODUCTION

(1.1) The Object of the Paper

The life span of oxide-cathode receiving valves has been studied by the manufacturers and large-scale users of valves for many years, but the subject to-day is almost devoid of literature. The object of the paper is to collect relevant published information on oxide cathodes which may have a bearing on life span, to supplement this with information derived from the laboratories of the Post Office Research Station and to attempt to integrate the whole into a working-life model of a typical oxide-cathode receiving valve.

Reasons for the paucity of information on valve life are easy to discern: the life phenomenon is complicated by the superposition of a number of distinct effects which are complex in themselves, difficult to separate, and possible to study effectively only in isolation. Certain of these effects are now reasonably well understood and can be detected, separated and measured in working valves. It is along such analytical lines that the authors have studied the life-span problem, and they have found that the effects now known appear to be sufficient to account for some observed deteriorations. However, they have limited themselves so far to a close study of long-life valve phenomena, assuming that these reflect a slow-motion picture of the conditions that lead to the relatively rapid failure of valves of poorer quality. It is possible that this assumption is wrong and that additional effects will be found necessary to explain the deterioration of short-life valves. One such possibility is tentatively explored in Section 5.

(1.2) Stimulus to Research

A number of new engineering requirements have arisen during the past decade to stimulate interest in the problem of valve life. They fall into three general categories, which are worth recording as they indicate the broad and growing basis of interest in the problem:

(*a*) Valves for use in inaccessible situations.
(*b*) Valves for use in equipments employing large numbers of inter-dependent valves.
(*c*) Valves having a higher order of operating stability for use in d.c. amplifiers.

Examples are too obvious and numerous to require specific mention.

(1.3) Life Testing of Valves

A useful introduction to the complexities of the life problem is afforded by a brief study of the results of conventional life-testing. Such tests are conducted by the valve manufacturers and by certain large-scale users of valves. Tests by the manufacturers are usually short-term ones—of 200–500-h duration—and are designed to maintain production quality. Such testing techniques have recently been described by Brewer.* Tests by the large-scale users, e.g. telephone administrations, are usually long-term ones in which the valve is run to an arbitrarily selected state of deterioration known as "end-of-life." In both systems the valves are tested in batches and are run under fixed conditions within specified ratings. Deterioration is observed by regular measurements of anode current or mutual conductance, i.e. tests are carried out under normal space-charge-limited operating conditions.

Long-term testing has been undertaken by the telephone administrations for the past 25 years and has given rise to useful information. Recently, however, there has been a revision of feeling within the Post Office against the conventional technique, and it has now been largely superseded by more novel methods. The circumstances leading up to this change of technique are interesting and may be worthy of brief mention.

During the war years it became the fashion in England for different manufacturers to make valve types to common performance specifications. Tests of a popular type of h.f. pentode from three separate manufacturing sources showed extraordinarily wide variations in life span, details of which are set out below:

Valve type: High-slope h.f. pentode with indirectly-heated oxide cathode.
Batch size: 12 valves.
Life span: Source A 4 000 h (all valves).
Source B 1 000–10 000 h (all valves).
Source C 40 000 h (all valves).

The authors are at the Post Office Research Station, Electronics Division.

* BREWER, R.: "Radio Valve Life Testing," *Proceedings I.E.E.*, 1951, 98, Part III, p. 269.

Clearly this result leaves the user in some difficulty; not only must he life-test all types in which he is interested, but he must also now test each manufacturer's variant of any type common to several manufacturers.

At this stage an even greater difficulty was encountered. The life spans of batches of a valve type made at different times by one manufacturer were compared: the first batch had a life in excess of 20 000 h, whilst the second one, made two years later, had a life of less than 3 000 h.

This last result leaves the user in an untenable position in regard to his conduct of life tests. Any life-test result can be considered as applicable only to the particular manufacturing run from which the test batch is taken. Such a drastic restriction confirmed the Post Office in its decision to cease large-scale tests of the conventional kind.

(1.4) Problems of Valve Life

It seems to the authors that two broad problems must be solved before the user can hope to achieve an effective control over the quality of his valves. These problems will now be briefly considered.

First, the producer must gain a reasonable control over the life span of his valves. Not only must life span be regular for a common valve coming from different sources, but it must also be sufficiently long to convince the user that he is getting all that he can reasonably expect. This statement leads to the difficult question as to what may be regarded as reasonable life in a valve. A study of life-test records shows that modern receiving valves rarely have a life of less than 2 000 h. At the other end of the scale, however, records show that modern valves with an average life of 50 000–70 000 h have been produced and that life spans in excess of 20 000 h are not uncommon. In the light of these figures, the authors venture the opinion that, when the problems of valve processing are more clearly understood than they are at present, a life of 30 000–40 000 h might be regarded as reasonable for a modern receiving valve. The key to the problem clearly lies in a greater knowledge of the basic factors that affect valve life.

The second problem lies in the necessity for developing some measure for assessing the life of a valve from short-term tests. A useful short-term test might be regarded as one which gives an assessment of life-span in about one-tenth of the span itself. A more desirable solution would, of course, be a single "spot" test to determine life or perhaps a particular aspect of life. Such a solution is not beyond the bounds of possibility.

The life-prediction technique is required by the user to assess the value of large-scale purchases and by the producer to determine the merits of supposed improvements in processing.

Both problems are too complex and too interdependent to encourage any hope of a quick or final solution. At the best, we must expect to proceed by partial solutions each of which, however, may presumably result in improved life-span. Some of the efforts directed towards such solutions are described in Sections 2–5.

(1.5) Classification of Valve Failures

A convenient method of classifying valve faults is to separate them in two broad divisions, namely functional failures and cathode failures.

Functional failures are frequently concerned with some form of mechanical derangement. Typical examples are burnt-out heaters, glassware breakages, electrode open- and short-circuits, etc. Other forms of functional failure are concerned with the breakdown of certain electrical insulations and with the growth of electron emission from certain components. The elimination of functional failures would result in valves having a high probability of a life of at least 1 000 h. Such hypothetical valves are now being described by development engineers in England as "reliable" valves. The production of reliable valves is largely a problem of economics and is probably within the compass of existing engineering skill. This view is supported by some interesting figures on functional failure given to us by Mr. W. T. Gibson. A batch of pentode valves, specifically designed for freedom from functional failure, ran for 2 000 h with only two failures among 1 011 samples.

Cathode failure is concerned with the several ways in which the oxide and its supporting core change with time to the detriment of the valve's performance. The cause and effect of these changes are amongst the more intractable problems of present-day applied physics. Subsequent Sections of the paper deal with various aspects of the problem as they now appear to the authors.

(1.6) Experimental Valves

It will be convenient at this stage to indicate the types of valve which are used for some of the experimental work described in the paper. All the valves mentioned are of the indirectly-heated oxide-cathode type, usually in pentode form although other electrode arrangements are employed in appropriate circumstances. The more common types used are the high-slope h.f. pentodes known as the CV138 and the CV1065. These valves have been drawn from various manufacturing sources. A valve which is also used is the Post Office 6P4 type, a version of the CV138 type made at the Post Office Research Station for experimental work on valve life.

Essential data on the 6P4 type are as follows:

Operation characteristics: Similar to those of the CV138 type.
Cathode core: Nickel containing 0·1% silicon and 0·07% magnesium.
Cathode material: Derived from equimolar co-precipitated barium and strontium carbonates with the conventional binder.

In Section 2, frequent mention will be made of the operation of the valves at different cathode temperatures. It is convenient for engineers to consider cathode temperature in terms of applied heater voltage, and this course will therefore be followed. Fig. 1 shows a typical relationship between applied heater voltage and cathode temperature for the 6P4-type valve.

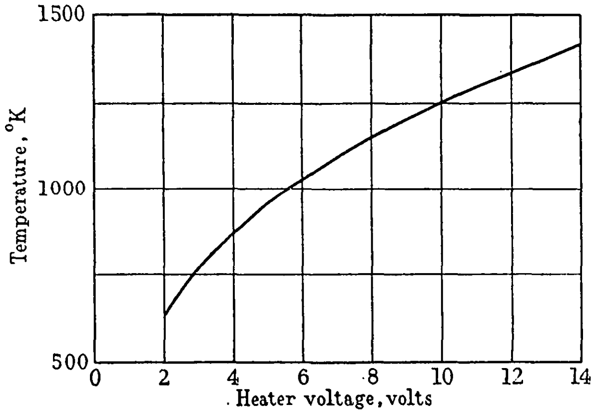

Fig. 1.—Heater-voltage/cathode-temperature relation for an average 6P4 valve.

(1.7) The Oxide-Cathode Model

The model of the oxide cathode adopted in the paper is the conventional one in which the oxide is regarded as a "reduction" semi-conductor of the n-type carrying an excess of the electro-positive elements. The excess elements are barium and strontium metals which are bound in the disturbed lattice of barium-strontium oxide in such a way that they are not subject to free evaporation at normal running temperatures (approximately 1 000° K). They are, however, open to attack from certain gases, and the ensuing reactions decrease both the electrical conductivity and electron emission from the cathode.

(2) FAILURES OF CATHODES UNDER GAS ATTACK

(2.1) The General Phenomena

(2.1.1) Early Work on Cathode Poisoning.

High-vacuum technique was in its infancy when Wehnelt invented the oxide cathode in 1903. It is not surprising, therefore, to find that much of the earlier work on the cathode was concerned with its behaviour in the presence of residual gases. Widespread literature arose from these studies which frequently showed an incompatibility reflecting the immature technique of the times. However, general agreement seems to have been reached that hydrogen and the inert gases had no deleterious effect on the cathode, whereas oxygen, water vapour, etc., had a de-activating or poisoning effect. These early studies have been reviewed by Reimann.[1]

With the application of chemi-sorption methods to aid the vacuum pump, an immense improvement was staged in the preparation of the oxide-cathode valve. The use of magnesium and barium getters enabled experimenter and valve maker alike to achieve a vacuum so high that it approached the limits of measurability. Under this stimulus the oxide cathode prospered and the output of literature on cathode poisoning fell almost to vanishing point. Such was the position around the years 1930–40. During the past decade, however, interest has revived and recent work has been reviewed by Herrmann and Wagener.[2] It now appears that most modern barium-gettered valves still retain minute traces of gas which adversely affect life.

(2.1.2) Measurement of Residual Gas Pressure in Valves.

The multi-electrode valve is capable of measuring its own residual gas pressure. The passage of electrons from cathode to anode results in the formation of positive ions whenever an electron makes a suitable encounter with a wandering molecule or atom of residual gas. Such positive ions migrate to the negative control-grid and cathode and set up a reverse grid-current. The residual gas pressure p (mm Hg) can be derived from this grid current. It is sometimes convenient, however, to express the pressure indirectly in the form of a vacuum factor k thus:

$$k = I_{rg}/I_a \text{ micromicroamp/milliamp} \quad . \quad . \quad . \quad (1)$$

where I_{rg} = Reverse grid-current in micromicroamp.

and I_a = Anode current in milliamp.

A simple proportionality exists between the pressure p and the vacuum factor k, namely:

$$k = cp \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The constant c defines the valve geometry in a particular case; it is settled for a valve type by simultaneous measurement of p and k on a single sample. The determination is carried out on a vacuum pump fitted with a fine leak valve and a calibrated ionization gauge.

The pressure in modern valves is between 1×10^{-9} and 1×10^{-4} mm Hg, whilst their vacuum factor may be between 500 and 100 000 micromicroamp/milliamp.

(2.1.3) Gas in Modern Valves.

The behaviour of gas in modern valves has been studied in some detail at the Post Office Research Station during the past four years. Some of this work[3, 4, 5, 6] has been published but the bulk of results is still in the form of current records. This and subsequent Subsections review the present position.

The first problem to be examined was the way in which gas pressure, or vacuum factor, changed during the life of a valve. Many oxide-cathode valves of triode or pentode form were examined and a consistent relationship was found to exist between the vacuum factor, k, and the time of operation, t. A typical example of a k/t characteristic is shown in Fig. 2.

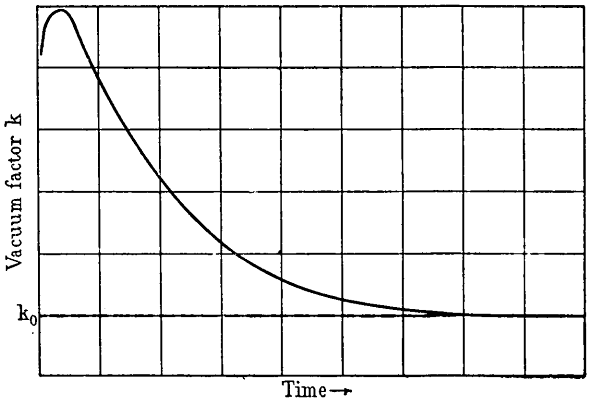

Fig. 2.—A typical vacuum-factor characteristic.

From such characteristics the following information was derived:

(a) All normal valves examined showed the same roughly exponential form of function: $k = f(t)$.

(b) The vacuum factor, k, of all normal valves fell to nearly the same value k_0 irrespective of valve type. The constant k_0 was called the residual vacuum factor.

(c) Once the residual vacuum factor, k_0, had been reached, the apparent pressure remained unchanged for indefinite periods of running.

(d) The only apparent differences between individual valves lay in the magnitude of the area enclosed between the curves $k = f(t)$ and $k = k_0$. This "gas" integral

$$\int_0^\infty k \, . \, dt$$

is a measure of the ionized gas which is driven into the cathode.

(e) A comparative study of two batches of a common valve showed that the short-life batch (approximately 3 000 h) had a large gas integral whereas the long-life batch (approximately 25 000 h) had a small one.

Fig. 3 shows typical examples of k/t characteristics.

From results such as these, the conclusion was reached that residual gas is one of the primary causes of cathode failure in valves.

This conclusion gives rise to the obvious question as to why any residual gas exists in the valve since it has already been inferred that a barium getter is capable of reducing pressure to the limit of measurement. The authors attempt to answer this question in Section 2.4.4, but they merely state here that a barium getter is capable of absorbing all the residual gas in a normal valve provided that suitable contact is made between gas and getter. The problem is one of association—not of getter capacity.

(2.1.4) The Residual Vacuum Factor k_0.

Brief mention must be made of the residual vacuum factor, k_0, since its correct interpretation is essential to vacuum measurement in valves. Investigation has shown that the factor is defined completely as a function of anode voltage, anode

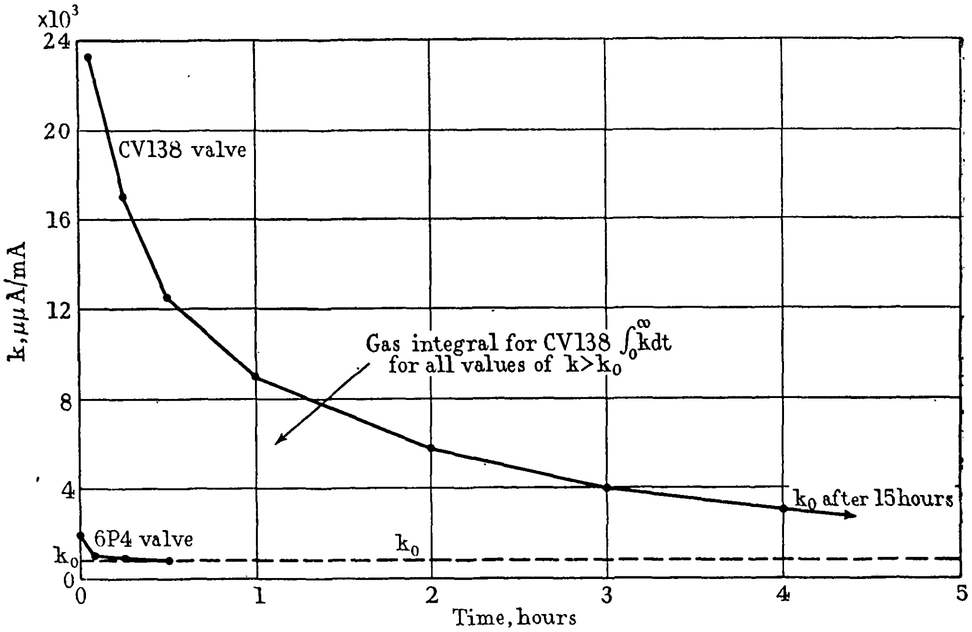

Fig. 3.—Gas integrals for two batches of a common valve type.
$V_a = V_{g2} = 250$ volts.

material and physical size of the positive-ion collector. The most important relation is that of the anode voltage:

$$k_0 = f(V_a)$$

which is shown as a typical example in Fig. 4. The quantities indicated in the example are typical for a pentode with a 2-watt cathode and a nickel anode.

At first sight it seemed that the shape of the lower half of the characteristic ($<$ 90 volts) was probably due to a normal ionization effect, but close investigation showed that both parts of the characteristic were due to the emission of photo-electrons from the grid under the impulse of soft X-rays generated at the electron-bombarded anode surface.[7,8] The voltage at which the discontinuity occurred was found to be constant for anodes of nickel, tantalum and thorium; change of anode material merely altered the slopes of the two parts of the characteristic. The cause of the discontinuity appears to lie in a change of the energy level at which the X-rays are generated; this might be expected with nickel, tantalum and thorium at about 90 volts. Measurements showed that more than 98% of the reverse grid-current observed under k_0 conditions was due to X-ray irradiation and less than 2% to true gas ions.

Work on these lines led the authors to estimate the true pressure in working valves to be lower than $1 \cdot 0 \times 10^{-9}$ mm Hg under k_0 conditions. The ultimate pressure in working valves has yet to be measured.

(2.1.5) Conclusions.

During the working life of the valve, traces of residual gas, which have escaped contact with the getter, are driven into the cathode in ionized form. This continued absorption by getter and cathode results in a drop of pressure to unmeasured limits and causes cathode deterioration by gas poisoning.

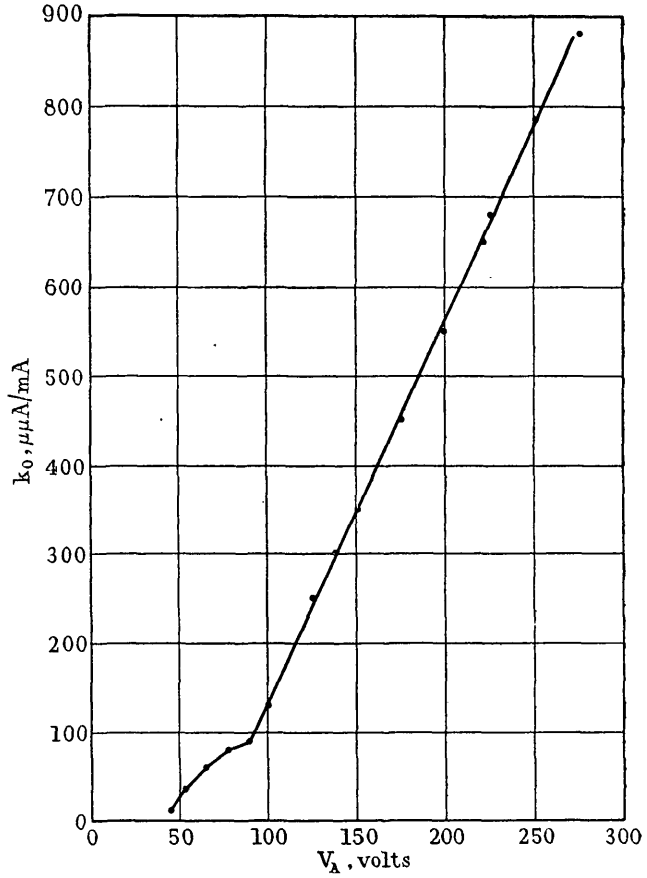

Fig. 4.—Example of a k_0/V_A characteristic.

(2.2) Total Emission Studies

The primary effect of gas on the cathode surface consists of a deterioration in the rate of emission of electrons. If any attempt is to be made to solve the second of the two main problems postulated in the Introduction, namely short-term assessment of valve life, it will be essential to measure this deterioration in electron emission as accurately as possible. If this emission is space-charge-limited the deterioration is masked to a considerable extent by the space charge itself. Only if the total or temperature-limited emission is measured can the full effects of gas attack on the cathode surface be detected quickly. For these reasons it was decided to attempt to measure the total emission of valve cathodes during life.

(2.2.1) Experimental.

Choice of Method.

In order to measure total electron-emission at normal cathode temperatures, there is no alternative to the use of a high-voltage-pulse technique; d.c. measurements at these temperatures would cause excessive heat dissipation. D.C. measurements at acceptable power values are practicable only if the cathode temperature is considerably reduced. For both pulse and low-temperature d.c. methods it is essential that the measurement should not damage the valve for normal operation and also, if possible, that the measured emission should be simply related to that existing under space-charge-limited conditions.

There is evidence[5] that film breakdown occurs with collector voltages greater than about 6 volts. The products of the breakdown are damaging to the cathode, particularly if the collector voltage exceeds the ionization voltage:[3] cathode damage ascribed to this cause has been observed with a pulse technique. In addition, the resulting changes in ion concentration on the cathode surface will almost certainly exclude a simple relation between measured emission and that under space-charge conditions.

If the low-temperature d.c. method is used, the conditions employed ($V_h = 2$ volts, $V_{g1} = +5$ volts, other electrodes earthed and $I_{g1} \simeq 1$ mA) are such that damage to the cathode does not occur. There is no ionic bombardment, no film breakdown on the collector, no excessive heat dissipation and consequently no release of gas. As in the pulse case, the relation of the measured emission to the emission under space-charge conditions is not known, but the simplicity and repeatability of the measurements and the absence of damage to the cathode has enabled some correlation to be found between actual changes in low-temperature emission and predicted changes in space-charge-limited life. For these reasons the low-temperature method has been preferred.

Limitations of Low-Temperature-Emission Measurement.

The limitations of low-temperature-emission measurement as a means for assessing behaviour at normal temperatures lie in the problem of extrapolation and also in the restrictions imposed by the nature of the measurement itself. The unreliability of extrapolating the Richardson line from the measuring temperature (about 700° K) to normal temperatures (about 1 000° K) has perhaps been emphasized in recent works on conductivity. They show a discontinuity in the conductivity/temperature characteristic somewhere in the region of 800° K. In view of the relation between conductivity and emission, it is possible that a similar discontinuity may exist in the Richardson line.

A better case can be made for the qualitative equivalence of proportional changes at low and normal temperatures, and this has been the subject of experimental work mentioned below. The problem of quantitative equivalence is considered later, but at this stage the use of total-emission studies in life testing is restricted to qualitative concepts.

The restrictions imposed by the measurement itself arise from the need for ensuring that the emission measured is really total, and not limited by space charge or retarding field. In addition, the reduction in temperature and the change in electrode voltages prior to the measurement must not affect the physical state of the cathode. In particular, the ionic equilibrium established during the preceding period of space-charge-limited operation should not be disturbed.

A collector voltage, V_{g1}, of + 5 volts will exclude, in most cases, the possibility of a retarding field, and with this voltage the collector current should not be allowed to exceed 5 mA with most modern indirectly-heated receiving valves. This excludes space-charge limitation and involves a heater voltage not greater than about 2·6 volts for new valves with normal 6·3-volt heaters.

In order to maintain the ionic equilibrium within the cathode, the reduction in temperature to the measuring conditions should "freeze" the ions in their sites. This does substantially happen at a cathode temperature of 700° K (corresponding to $V_h \simeq 2$ volts), and this temperature is chosen for the measurement. A simple experiment has shown an increase in freedom of ionic or atomic movement by a factor of 10 as the heater voltage increases from 2 to 3 volts, and by a further factor of 40 for a further increase in heater voltage from 3 to 4 volts.

The collector voltage of + 5 volts contributes to the maintenance of ionic equilibrium by excluding ionization outside the cathode and by preventing film breakdown on the collector.

Experimental Technique.

Measurements of total emission during life are made by periodically withdrawing the valves from the life-test racks, where they are running under space-charge-limited conditions, and inserting them in a simple d.c. test circuit. In view of the high dependence of total emission upon cathode temperature, it is essential that the latter should be the same for all measurements. Owing to the impracticability of temperature measurements, control of heater power to within close limits is accepted as a substitute. These limits can be estimated from the following empirical relations, which have been found to hold good in the range $V_h = 2\cdot 0 \pm 0\cdot 1$ volts:

$$\frac{\Delta I_s}{I_s} = \frac{8\Delta P_h}{P_h} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and

$$\frac{\Delta I_s}{I_s} = \frac{24\Delta I_h}{I_h} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where I_s is the total emission.

If the heater resistance remains constant, it is possible to control heater current rather than heater power, and from eqn. (4) it follows that to obtain an accuracy of 1% in the measurement of I_s, I_h must be controlled within 0·1%. This necessitates the use of a potentiometer. Use of constant heater-current conveniently enables the heaters of several valves to be run in series for the emission measurement, and it also obviates errors due to contact resistance at the valve pins. There is, however, some possibility of changes in heater resistance during life, at least for some types of heater wire, and if these occur there is no alternative to either measurements at, or corrections to, constant heater-power.

During the experiments it was also found that the emission depended on the constancy of the ambient temperature to the extent of an increase in emission of some 0·3–1·0% per deg C. This variation can be eliminated by the use of a constant-temperature enclosure, but in view of the large changes in emission which occur during valve life the correction is not considered essential.

It was found that a period of a few hours must be allowed for the emission to reach equilibrium, and during this period a fall of as much as 4% may occur. The effect is thought to be due to penetration of the collector field into the cathode, as suggested by Morgulis,[10] who records an almost instantaneous change in electron emission, which, of course, is not seen in d.c. measurements. The delayed effect recorded here is a new feature of the penetrating-field phenomena revealed by these emission studies and is probably due to disturbance of the ionic equilibrium inside the cathode by the penetrating field.

Despite precise control of the measuring conditions, irregularities in the total-emission/time characteristics do occur and are probably due, in most cases, to instability of the operating conditions on the life-test racks. In some cases the measured emission fluctuates about a mean value—a change of ± 4% in heater voltage has been shown to produce a change in emission of ± 2% (at constant temperature under measurement conditions) if the heater voltage change persists for an hour prior to the measurement. With valves having a high gas-content, a small time-limited change in life-test conditions may produce a cumulative deterioration in emission up to the point of complete collapse. Apart from these causes of irregularity, the measurement itself has a repeatability of the order of ± 0·2%.

(2.2.2) **Results of Tests.**

Mean and typical total-emission/time characteristics for several batches of valves are given in Fig. 5. The life-test-rack conditions were $V_h = 5\cdot5$ volts, $V_{g2} = 250$ volts, $V_a = 150$ or 250 volts and $I_a \simeq 6$ mA. The batches of 6P4 and CV1065(A) valves were large (72 valves per batch) whereas the other batches were small (4 valves per batch). The CV1065(A) and (B) valves were produced by two commercial manufacturers, whilst the 6P4 and 6Te 4B valves were produced by the Post Office Research Station. The total-emission and space-charge-limited results for one type CV1065 (B) valve are shown in Fig. 6.

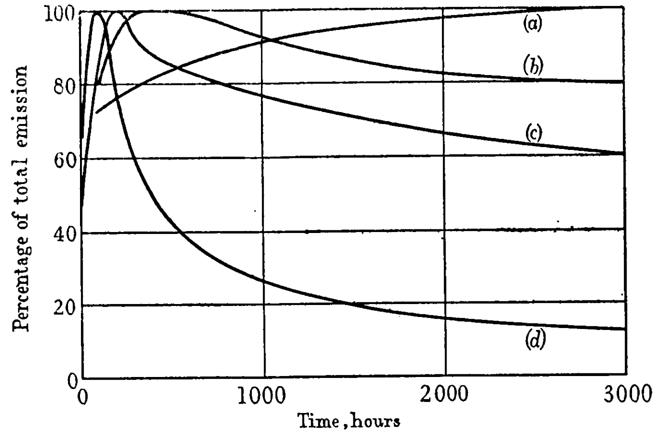

Fig. 5.—Mean and typical total-emission-time characteristics.

(a) Typical 6P4.
(b) Typical 6P4; mean 6Te4B.
(c) Mean CV1065(A).
(d) Mean CV1065(B).

Some idea of the spread of the results about the mean curves illustrated is given by the fact that, in the batch of type CV1065 (A) valves, 85% of the valves after 3 000 h had emissions between ± 12% (of the maximum emission attained) of the mean.

The following information is available on the four valve types in Fig. 5 derived from longer-period life tests. The type CV1065 (B) has a high probability of failure before 6 000 h, the failure point being arbitrarily assumed to occur when the mutual conductance, g_m, falls by 30%, under conditions of constant cathode current. The type CV1065 (A) will probably still be satisfactory after 60 000 h; the mutual conductance will then be some 83% of its original value. The types 6P4 and 6Te 4B are still satisfactory after 8 000 and 10 000 h respectively, and their extended life test is still in progress.

It may be mentioned here that plotting the results of the low-temperature total-emission tests on a percentage basis is justified by the fact that the average percentage rate of deterioration is substantially independent of the actual maximum emission attained.

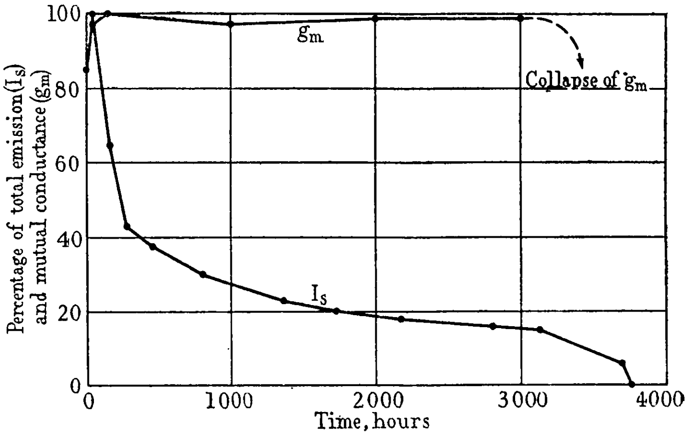

Fig. 6.—Total emission and space-charge-limited life characteristics for a CV1065(B).

(2.2.3) **Correlation of Low-Temperature-Emission Measurements with Space-Charge-Limited Operation.**

Qualitative Correlation.

The results recorded in Section 2.2.2 can immediately be used on a qualitative basis. It can be argued that any valve with an emission/time characteristic better than the mean curve for valves of type CV1065 (A) probably will not fail before 60 000 h. Conversely, any valve with a characteristic like those of type CV1065 (B) probably will fail before 6 000 h. In making these assertions, it is implied that the cause of failure is the one which produces the characteristics on which the assertion is based, namely gas attack on the surface of the cathode. The assertions also support the concept of the qualitative equivalence of proportional changes at low and normal temperatures.

It is certain that gas is at least a primary cause of early valve failure, and therefore the second assertion is almost certainly true. On the other hand, as is indicated later in the paper, there are definitely other causes of valve failure which become effective later in life. Consequently the probability in the first assertion is not so high as in the second. Nevertheless the characteristics have in practice provided a very useful yardstick with which to assess the merits of different valve batches.

Quantitative Correlation.

On the assumption of a quantitative equivalence of proportional changes of total emission at low and normal temperatures, use can be made of the Langmuir relation to calculate the consequent changes in space-charge-limited current or conductance:

$$I = \frac{2\cdot335\ 10^{-6}(V - V_m)^{\frac{3}{2}}}{(d - x_m)^2}\left[1 + \frac{T^{\frac{1}{2}}}{40\cdot3(V - V_m)^{\frac{1}{2}}}\right] \quad . \qquad (5)$$

where I = Space-charge-limited diode current, amp/m^2.
V = collector voltage, volts.
d = Cathode-collector distance, metres.
x_m = Distance of space-charge voltage minimum in front of cathode, metres.
V_m = Negative minimum voltage, volts.
T = Cathode temperature, deg K.

(The total emission, I_s, occurs in the expressions for V_m and x_m).

Calculations based directly on eqn. (5) are difficult, but an analysis has been made by Ferris[11] which greatly simplifies the mathematics. The resultant correlation between emission and space-charge-limited current and conductance is given in Fig. 7.

A ratio of $100\% I_s/100\% I$ equal to 1 200 was chosen for the constant-current curve in Fig. 7, and a ratio equal to 400 for the constant-bias curve. These correspond to space-charge-limited current densities of the order of 8 mA/cm^2 and 24 mA/cm^2, respectively, for the high-slope pentodes (CV138 or 6P4) considered here. It will be seen that, if the conductance is measured at constant space current, as it is in our life tests, the emission can fall to 1% of its original value before the conductance falls below 95% of its original value (cf. Fig. 6 at a constant current-density of 6 mA/cm^2).

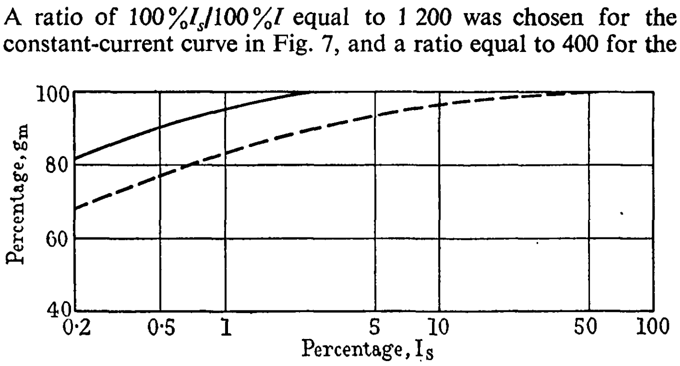

Fig. 7.—Correlation between total emission and space-charge-limited mutual conductance for a valve.

– – – – V_{g1} (effective) constant.
——— I_k constant.

As there is no essential difference between the diode and pentode cases, these results make it clear that, for any of the four valve types in Fig. 5, the changes in surface total-emission will have no measurable effect on g_m—at least during the first 3 000 h. However, the proviso must be made that the fall in emission is an effect distributed uniformly over the cathode surface. If the fall in emission is due to a total blocking of emission over patches of the cathode, and if the patches are large enough to disturb the smoothness of the space charge, then the mutual conductance will tend to fall with total emission on a proportional basis.

In connection with these arguments, the results of measurements on valves of type CV1065 (A) at 56 000 h indicate that the total emission is still some 10–20% of its probable maximum value (the emission-measuring technique was not developed when the life test was started). As g_m had fallen by some 17%, it is clear that a distributed fall in total emission is inadequate to explain the decay. It is suggested later in the paper that it is more probable that the deterioration is largely due to interface resistance.

The attempt at some form of quantitative correlation has led to the following conclusions. First, in view of the extremely low value of total emission which may be reached before g_m is appreciably affected on the basis of the Langmuir relation, it is very likely that some of the other causes of failure described below will have operated before any correlation can be made between distributed surface emission changes and changes in g_m. Secondly, it is not sufficient to know that the surface emission has fallen by a certain amount—it is also necessary to know whether the fall is an evenly distributed effect or a patching one. In the latter case the size of the patches is important. It is believed that there is no such thing as a true distributed effect but rather that, if the patches are small enough, the resultant will be equivalent to even distribution.[12] It is true that gas attack will produce the effect of even distribution and that larger-size patching must be attributed to the phenomena described in Section 5. Thirdly, total-emission studies of the type described are inadequate as a comprehensive criterion of valve merit, and a further development in testing is essential. This is considered in Section 2.3.

(2.3) Resistivity as a Function of Total Emission

In Section 2.3 it has been assumed that gas attack on an oxide cathode results solely in deterioration of surface emission. It is certain, however, that the bulk of the cathode will also be affected —either by penetration of the gas or by movement of active barium to the surface to re-establish concentration equilibrium. Any form of de-activation of the bulk of the cathode will result in an increase in cathode resistance and consequently in a fall in g_m, owing to negative feedback (see Section 3.1). It was therefore decided to attempt to develop the total-emission studies described in Section 2.2 in order, if possible, to derive some estimate of the cathode resistance.

(2.3.1) Method of Measurement.

A method of measuring cathode resistance has been developed and will be described in detail in a later publication. Briefly, it consists of a derivation of resistance from the curve of $\log I_{g1}$ plotted against V_{g1} over the ranges of retarding-field emission and total emission. This curve is the one generally used for determination of the contact potential between grid and cathode and will be referred to as the contact-potential curve.

Resistance derivations from the retarding-field region of the contact-potential curve have been made by Miller and Dalman in unpublished work. They use the relation

$$R_k = \frac{T}{11\,600 I_{g1}}\left\{\frac{5\,040}{T\left[\dfrac{d\,(\log I_{g1})}{d\quad V_{g1}}\right]} - 1\right\} \quad . \quad . \quad (6)$$

where R_k = cathode resistance. There are experimental difficulties in applying eqn. 6 which arise from the need to know T, the cathode temperature, and also from the fact that $d\,(\log I_{g1})/dV_{g1}$ must be measured accurately in the region of low retarding-field currents—of the order of 50 microamp or less.

The method described here, however, depends essentially on the curvature of the knee of the contact-potential curve and can be understood empirically from the diagram in Fig. 8. The total resistance of cathode plus microammeter is given by the equation

$$R + R_k = (V_0 - V_{cp})/I_0 \quad . \quad . \quad . \quad . \quad . \quad (7)$$

from which the cathode resistance R_k is easily determined.

It is appreciated that the shape of the contact-potential characteristic is the subject of controversy, but it is considered that the experimental evidence described below supports the view that the shape is closely related to the resistance of the cathode.

(2.3.2) Total-Emission/Resistance Relationship.

The results obtained from use of the method described above are most conveniently summarized in two curves The first, Fig. 9, is a curve of $\log I_0$ plotted against $\log R_k$ for one valve at any instant during its life; it is derived from a family of contact-potential curves taken at cathode temperatures ranging from 620 to 800° K.

The equation of the full line ABC is

$$\log I_0 = -\log R_k + 6{\cdot}2 \quad . \quad . \quad . \quad . \quad (8)$$

where I_0 is measured in microamp and R_k in ohms. The $\log I_0/\log R_k$ curve of all valves so far tested roughly coincides with this line for values of I_0 less than about 1 mA; there are minor deviations amounting to a maximum of $\pm 0{\cdot}08$ on the $\log R_k$ scale. The 45° slope of the full line is in agreement with the proportionality of emission and conductivity described by Hannay, MacNair and White.[24] For values of I_0 greater than 1 mA, the plot follows the broken curve rather than the full one. This deviation is identified with the interface resistance. A change in slope due to interface resistance is reasonable and, in addition, gives some confidence that Fig. 9 is not merely a curve of $\log I_0$ plotted against $\log 1/I_0$ [cf. eqn. (7)].

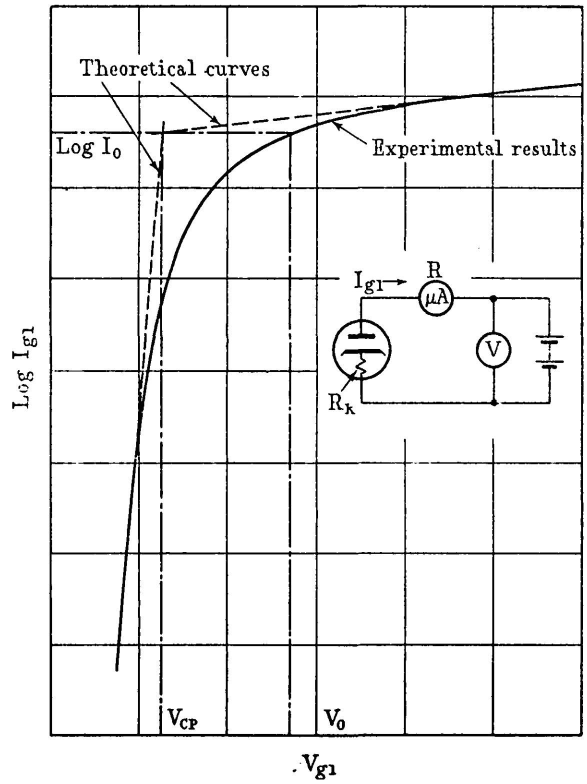

Fig. 8.—Derivation of cathode resistance from the contact-potential curve.

$R + R_k = (V_0 - V_{CP})/I_0$.

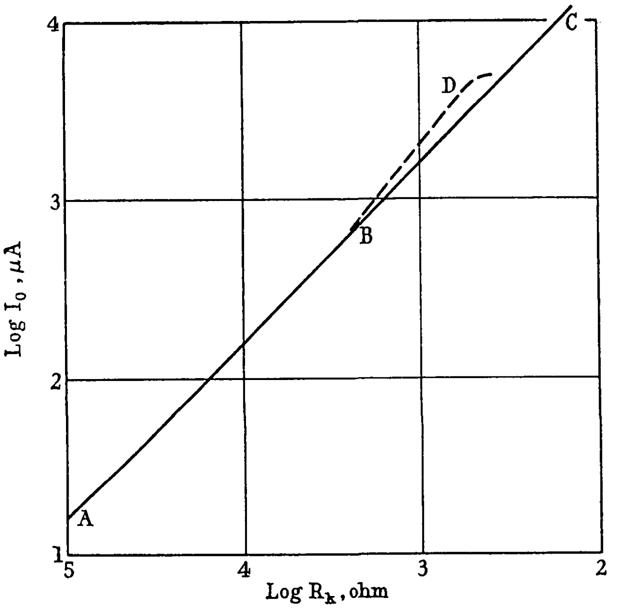

Fig. 9.—Total-emission/cathode-resistance relationship.

As the age of the valve increases, the point representing log I_0 and log R_k for any given heater power moves down the lines DB, BA.

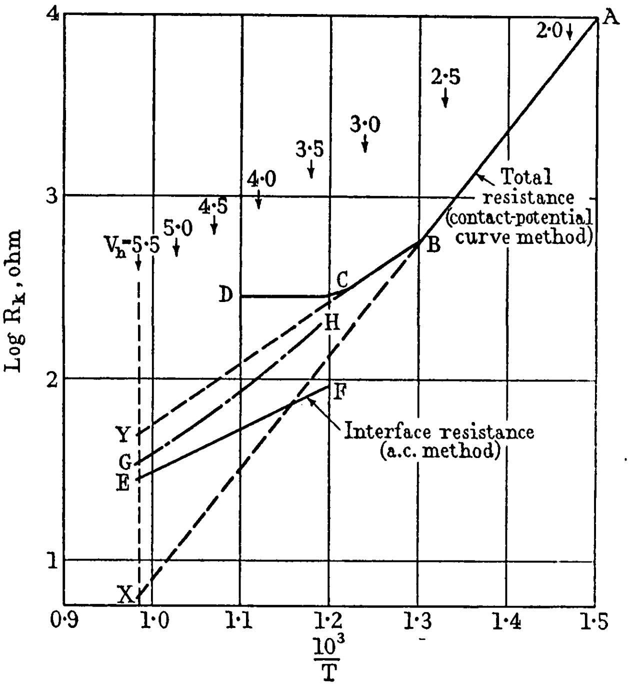

Fig. 10.—Cathode-resistance/temperature relationship for a CV1065(A).

(2.3.3) **Resistance/Temperature Relationship.**

If the relation between cathode temperature and heater power is known, then log R_k can be plotted against $1/T$. A typical curve ABCD is shown in Fig. 10 for a CV1065 (A) valve after 60 000 h. The part CD of the curve is due to the onset of space-charge limitation and may be neglected. The part ABC is regarded as the resultant characteristic of two resistances in series—that of the interface and that of the cathode bulk. The bulk supervenes over the range AB, whilst the interface supervenes over the range BC. In view of the magnitude of the bulk resistance at low temperatures, extrapolation of AB to X will give a measure of the bulk resistance at $T = 1\,015°$ K. Similarly, extrapolation of BC to Y will give a measure of the total resistance, and XY a measure of the interface. The line EF gives the interface-resistance/temperature characteristic for the same valve at the same time determined directly by the method described in Section 3.2.1. The sum of EF and BX gives the broken curve GH, which does not deviate markedly from BY considering the very different experimental techniques adopted and the possible source of discrepancy referred to below.*

This agreement holds for new valves of the same type where typical results using this method are as follows:

Total resistance:	4 ohms.
Interface resistance:	3 ohms.
Bulk resistance:	1 ohm.
Temperature:	1 000° K ($V_h = 5\cdot5$ volts).
Cathode area:	1 cm^2.

For some valves, however, the interface resistance determined by this method is considerably higher than that determined by the a.c. method described in Section 3.2.1. There is a possibility that the discrepancy may be used as a measure of the degree of patching of the cathode surface. A patch effect on the cathode surface, where the emission is reduced effectively to zero over certain areas, will decrease the measured emission by a factor k and will probably increase the resistance by the same factor. This will shift the whole log $R_k/\frac{1}{T}$ plot by an amount equal to log k parallel to the log R_k axis, producing an apparent increase in the interface resistance. Under the conditions appropriate to the a.c. method, the space charge may smooth out the effect of the smaller patches and the measured interface resistance would

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* More recent work has shown that, if a correction based on Langmuir's equation [eqn. (5)] is applied, even better agreement between GH and BY is obtained.

show little or no increase. Preliminary experimental results show that this hypothesis cannot be excluded; further reference is made to it in Section 5.

(2.3.4) **Application of the Method.**

The development of this supplementary aid to the assessment of expectation of valve life in no way invalidates the use of total-emission studies as described in Section 2. A vital factor in favour of the latter is still the speed with which a simple total-emission measurement may be made.

It is possible to use a curve similar to Fig. 9 in order to translate very-low-temperature-emission measurements into an estimate of the cathode bulk resistance at operating temperatures. In view of the fact that the interface resistance predominates at normal temperatures, however, such a procedure must be allied to the relatively quick measurements of interface resistance described in Section 3 in order to gain full information of the negative-feedback effect. A complete investigation is of course possible using the method described above, but the experimental work involved is excessive from the point of view of standard life-testing at regular intervals. Nevertheless, the additional information gained thereby makes the investigation worth while in special cases.

(2.4) **Processing Principles necessary for Avoidance of Gas Failure**

In a perfectly processed valve it appears probable that a cathode maintained at a suitable temperature will have an indefinitely long emission-life. The principal requirement of such a process is the achievement of a perfect vacuum in the valve before it enters service. To this end are directed the three basic operations of valve-making technique, namely pre-processing of piece parts, pumping and ageing. Each operation is designed to assist the one that follows it, and the culmination should be a closed system in which the only possible form of spatial movement is electronic. Present-day technique falls short of this ideal and always leaves a residuum of spatial atomic and ionic movement.

(2.4.1) **Pre-processing of Piece Parts.**

Pre-processing of piece parts is a well-established art and has been adequately described in the literature by Benjamin, Cosgrove and Warren,[13] and Espe and Knoll.[14] The main processes involved are washing, hydrogen stoving and vacuum outgassing of metal parts. So far as the authors' experience goes, these processes appear adequate, but they feel that further research on the physical-chemical reactions of glass and mica under thermal treatment would be rewarding.

(2.4.2) **Pumping.**

In the pumping process, the assembled valve is connected to some form of pump and its pressure reduced as rapidly as possible, the glassware of the valve being taken up to as high a temperature as possible (approximately 400° C), the carbonated cathode being converted thermally to the oxide form, and metal components being brought to a red heat by eddy-current heating; the valve is then sealed off. All large-scale valve-pumping techniques follow these general lines, and their application to commercial valve manufacture has been well described by Benjamin, Cosgrove and Warren. Differences in technique lie in the order and intensity of application of the several aspects of the process and in its duration. Commercial pumping schedules take about 5–10 min to complete and leave the sealed valve with a pressure of about 1×10^{-3} mm Hg. Laboratory schedules for valves of special importance may take several hours of pumping and give a sealed-off pressure of 1×10^{-6} mm Hg. Selection of a schedule has both economic and engineering aspects.

(2.4.3) **Gettering or Internal Pumping.**

Just before or just after the sealing of the valve, the getter is fired. The ensuing physical-chemical gettering action reduces the pressure rapidly, and the phenomenon may be regarded as a form of internal pumping. A getter may therefore be identified with a pumping speed which will depend on the pressure and nature of the pumped gas. Since the achievement of an adequate vacuum depends largely on the efficiency of gettering, some consideration must be given to types of getter and their characteristics.

There are two main types of getter, namely the flash getter, which is evaporated onto the glass envelope, and the coating getter, which consists of a metallic powder deposited on a component in the valve. Flash getters usually consist of barium or magnesium, and typical coating getters are zirconium and thorium. Coating getters require a considered thermal treatment within the valve before they become effective.

The quantities of gas taken up by some typical getters have been measured in the pressure range 1×10^{-2} to 1×10^{-3} mm Hg by Ehrke and Slack.[15] Some values are given in Table 1.

Table 1

Quantities of Gas taken up by Barium and Magnesium Getters (Bright Getter Deposits, Gas Pressure $\simeq 10^{-2}$ mm Hg)

Gas	Quantities of gas taken up	
	By magnesium	By barium
	micron × litres/mg	micron × litres/mg
Oxygen	20	15·2
Carbon dioxide	—	5·2
Hydrogen	—	87·5
Nitrogen	—	9·5

Since commercial valves are sealed off at a pressure of a few microns, these measured absorption figures might be considered as more than adequate to deal with the gas in a valve of some 50-cm^3 volume or less. In practice, however, difficulties arise from two separate causes which require consideration. First, the mechanism of gettering action at very low pressures is different from the simple chemical reaction between getter and gas molecule which occurs at the higher pressures employed in the measurements of Ehrke and Slack. Special conditions must be observed if gettering is to continue effectively at pressures below 1×10^{-6} mm Hg. Secondly, the problem of physically associating gas and getter becomes increasingly difficult as pressure falls to low values.

A considerable amount of work[16] has been undertaken at the Post Office Research Station on gettering efficiency and gettering mechanism at pressures of 1×10^{-6} mm Hg and lower. It appears that gas in the form of atoms is preferred for efficient gettering, the molecule and the positive ion contributing but little to the action. Experimental measurement of the positive-ion flow to a getter showed that the ion absorption was accounting for less than 1% of the required absorption necessary to explain an observed gettering rate. The occurrence of the atomic state in gettering action appears to have been first recognized by Reimann[17] in experiments at higher pressures.

The efficiency of the getter is inhibited by two factors: the re-formation of normal molecules, and flow resistance presented to the atoms on their way from the source to the getter. Owing to these factors, clear advantage is obtained by locating the getter as close as possible to the electron stream.

Gettering rates at pressures of three or more decades lower

Table 2

RATES OF GETTERING FOR DIFFERENT GASES

Getter	Temperature	O_2	CO	CO_2	H_2O	H_2	N_2
		cm³/sec	cm³/sec	cm³/sec	cm³/sec	cm³/sec	cm³/sec
Barium flash getter	$\simeq$ 300° K	1 000	1 250	3 000	2 300	250	80
Thorium coating getter	$\simeq$ 300° K	1 400	—	2 000	1 000	—	10
	950° K	1 500	2 400	3 000	250	45	35
Oxide cathode . .	$\simeq$ 300° K	1 000	—	—	—	—	—
	1 000° K	350	—	—	—	—	—
	1 250° K	$\leqslant$ 50	—	—	—	—	—

Pressures used for measurement: O_2, CO, CO_2, H_2O: $p \simeq 2 \times 10^{-7}$ mm Hg.
H_2, N_2: $p \simeq 2 \times 10^{-6}$ mm Hg.

than those used by Ehrke and Slack have now been measured by a new technique. Details of this work will be published in the near future, but Table 2 gives a selection of typical results.

It will be apparent from these figures that the known getters are capable of removing all gas in a valve down to the lowest measurable pressures. Improvement in the getter itself does not appear necessary at the present stage: what is essential is improvement in the application of the gettering action.

(2.4.4) The Ageing Process.

The last of the three basic processes leading to the finished valve is commonly described as "ageing," and the reactions that occur during this final phase are complex and only partially understood. One object of ageing, however, is clear—the finished product should have an enduring vacuum as near perfect as possible. This near-perfection of vacuum is sought in two separate and distinct ways. First, all absorbed gases on all internal surfaces must be maintained at a sufficiently high level of thermal energy to keep them moving spatially until they have permanently associated themselves with the getter. This action requires time, a sufficiently high temperature for all internal surfaces and an unrestricted path for the movement of atoms and molecules.

The second necessity lies in the complete breakdown of all barium and strontium compounds which will have formed on the electrodes during the high-temperature phase of cathode conversion. The properties of these surface films, mainly oxides and chlorides, are now understood in some detail. The films are quite stable at red heat and can be broken down only under the impact of electron bombardment. Completion of the process is reached when the film compounds are wholly converted to the metallic state—i.e. when the liberated oxygen and chlorine have been absorbed by the getter.

During these processes, which proceed concurrently, the pressure in the valve rises and the cathode itself tends to act as an auxiliary getter (see Table 2). To mitigate this inevitable but wholly undesirable action, the cathode is raised in temperature to about 1 250° K. This temperature increase has a twofold effect: it lowers the "accommodation coefficient" of the cathode surface to gas absorption and speeds up the diffusive flow of reducing agents from the cathode core to compensate for such excess barium as may be lost in the matrix by gas poisoning.

One point regarding the pressure rise during ageing may usefully be considered. It is known that, at low pressures, gas absorption is proportional to pressure, and it follows that cathode poisoning will likewise be a function of pressure. High pressure peaks should therefore be avoided, and the ideal ageing schedules would maintain a constant pressure throughout the process. In practical work, however, it is impossible to avoid peaks, but they can be kept low and roughly equal by a considered application of the thermal load. Continuous observation of the vacuum factor is useful in the design of efficient ageing schedules.

Ideally, the ageing process is continued until all spatial ionic, atomic and molecular movement has ceased and the cathode has achieved an adequate emission. For technical and economic reasons this ideal is rarely approached in commercial valves.

(2.4.5) Laboratory-Processed Valves.

Under laboratory conditions it is possible to control the three basic processes with some precision. It is of course impossible to recognize the end of spatial ionic movement in the ageing process on account of the k_0 state, but k_0 achievement is at least an assurance that pressure is at its lowest recognizable level. Pentodes of the 6P4 type have been made in some quantity at the Post Office Research Station, in a manner approaching the conditions set out in the previous Subsections. These experimental valves appear to have a very long emission-life.

(3) FAILURE OF CATHODES BY FORMATION OF A CATHODE-CORE RESISTIVE INTERFACE

(3.1) Introduction

It is now common knowledge that a resistive interface develops between the barium-strontium oxide matrix and the nickel core of conventional valves. Nickel cores usually contain about 0·05–0·10% of certain reducing agents (e.g. magnesium, silicon, etc.) to assist in the production of the excess barium required for the activation of the cathode. This reducing process,

$$Si + 2BaO \rightarrow SiO_2 + 2Ba \quad . \quad . \quad . \quad . \quad (9)$$

appears to be followed by some such reaction as,

$$SiO_2 + 2BaO \rightarrow Ba_2SiO_4 \quad . \quad . \quad . \quad . \quad (10)$$

This barium orthosilicate, forming a thin but compact layer between matrix and core, may be regarded as typical of the various interfaces observed experimentally by Rooksby,[18] Eisenstein,[19] Wright[20] and others. Core impurities known to produce interfaces are aluminium, magnesium, silicon and titanium.

Interface formation in practical valves may be readily recognized by dissolving the barium-strontium-oxide matrix from the core with dilute acetic acid. The seat of the interface shows up as a dull, matt etching in strong contrast to the bright nickel surface which has not been in contact with the matrix. Cores which contain no reducing impurities do not show such interface etchings. A typical example of an etch is shown in Fig. 11.

One effect of interface formation is to insert a series resistance in the cathode circuit, and this leads to the introduction of a negative-feedback phenomenon in triode or pentode valves. Eisenstein has considered this effect and expresses the opinion

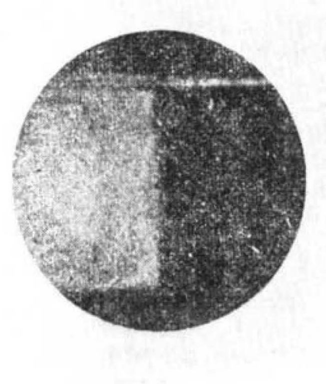

Fig. 11.—Cathode sleeve, showing interface layer on left-hand side (previously coated part).

that it is unlikely to cause common valve failure. The authors, however, take a different view and feel that, with the elimination of serious deterioration of emission, valve failure by interface growth may become commonplace.

(3.2) Some Experimental Observations

The curves in Fig. 7 show that the emission of normal oxide-cathodes may fall by over 90% without any appreciable change in mutual conductance. Measurements taken over a period of 3 000 h on a group of 6P4 valves, however, showed a fall of some 2–4% in mutual conductance although the total emission increased continuously over the period. This simultaneous rise of emission and fall of mutual conductance can be explained in terms of interface resistance. Thus, if the original mutual conductance is g_{m0}, then the insertion of a cathode resistance R will result in a modified mutual conductance g_m, where

$$g_m = \frac{g_{m0}}{1 + Rg_{m0}\alpha} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

and

$$\alpha = \frac{\text{cathode current}}{\text{anode current}} \simeq 1 \cdot 25$$

Assuming $g_{m0} = 4 \cdot 5$ mA/V for the 6P4 valve, then a series resistance of about 8 ohms is necessary to account for the fall of 4% in g_{m0}. Direct measurement of interface resistance for the batch gave values of 2–8 ohms.

A few test results are set out in Table 3, relating changes in g_m and R for individual 6P4 valves over a test period of 6 000 h. In these cases it is concluded that the four samples are failing rapidly from interface feedback at an average rate of 1% fall in g_m per 1 000 h.

Table 3

Changes in g_m and R for Individual 6P4 Valves over a Test Period of 6 000 h

Valve No.	I_s^o	I_s^t	g_m^o	g_m^t	R^c	R^m
	μA	μA	mA/V	mA/V	Ω	Ω
103/6	1 548	3 050	4·70	4·55	5·6	5·8
104/8	708	1 440	4·50	4·20	12·7	10·8
74/4	874	809	4·45	4·05	17·7	15
74/5	602	523	4·30	4·02	13·0	12

$I_s^o - I_s^t$ = Low-temperature total-emissions at beginning and end of test run.

$g_m^o - g_m^t$ = Mutual conductances at beginning and end of test run.

R^m = Measured change in interface resistance.

R^c = Calculated resistance to cause observed fall in mutual conductance.

A further case of failure may be quoted as it involves larger changes in g_m and R. Samples taken from a large-stock batch of CV1065 type valves were rack-tested for 60 000 h and a fall of 15–20% in mutual conductance was observed. The estimated fall in total emission over the test period was 85%—an amount insufficient to account for any appreciable change in mutual conductance. The interface resistances after 60 000 h were measured and found to cover the range 20–40 ohms. No measurements of interface resistance were taken when the valves were first placed on test, but measurements on new samples from the same stock batch gave values in the range 1–5 ohms. From these results it appears that 60–80% of the observed deteriorations in g_{mo} of the tested valves is due to interface-resistance feedback.

(3.3) Measurement of Interface Resistance

Measurement of interface resistance is likely to become one of the important valve measurements in the future. The measurement is based on the fact that the resistance is associated with a parallel-connected capacitance. Raudorf[21] has shown that, by measuring the gain of the test valve at three suitably spaced frequencies, it is possible to determine the values of both resistance and capacitance.

A modified technique of measurement having some advantage over Raudorf's arrangement has been developed at the Post Office Research Station. Only the resistance is measured but results are obtained conveniently, rapidly and with adequate accuracy. As the valve technique of measurement is still in the formative state, a brief description of these later developments may be of interest.

When the anode impedance of a valve is large compared with the load resistance, the gain is given with reasonable accuracy by $S = g_m R_L$, where S is the gain, g_m the mutual conductance and R_L the load resistance. If the only frequency-dependent element in the circuit is a resistance-capacitance combination (the interface) in the cathode lead, then, at sufficiently high frequencies,

$$S_\infty = g_m R_L \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

At very low frequencies,

$$S_0 = \frac{g_m R_L}{1 + g_m R\alpha} \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where R is the interface resistance.

If, at the low frequency, the anode load is increased to $R_L + R_X$ so that

$$S_0' = \frac{g_m(R_L + R_X)}{1 + g_m R\alpha} = S_\infty$$

Then

$$R = \frac{R_X}{S_\infty \alpha} \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

The choice of suitable test frequencies has to be a compromise dictated by the valve and associated circuit elements. In practice, frequencies of 10^7 and 10^4 c/s were found suitable.

The basic circuit requirements are shown in Fig. 12. The valve, V, under test is provided with variable bias which enables the cathode current, and hence the mutual conductance, to be adjusted smoothly and accurately. Components are selected to make the anode load, excluding the variable resistor R_X, the same at both test frequencies. The inductance, L is included at 10^7 c/s to offset anode stray capacitance.

The ratio

$$\frac{R_1 + 1/j\omega C_1}{R_2 + 1/j\omega C_2} = \frac{Z_1}{Z_2} \quad . \quad . \quad . \quad . \quad . \quad (15)$$

is also kept constant.

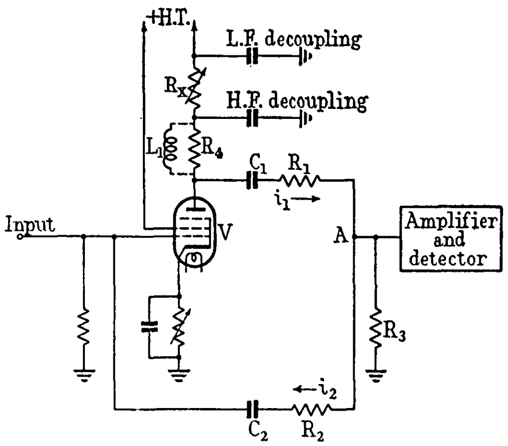

Fig. 12.—Basic circuit for interface measurements.

The variable resistor, R_X, which operates only at low frequency is assumed to be directly additive to the anode load. This is not strictly true, but provided R_4 and R_X are small compared with Z_1 the error will be small.

The input to and the output from the test valve are connected to the input stage of a high-gain amplifier-detector unit. The input voltage to the amplifier is the vector sum of the currents i_1 and i_2 flowing through R_3.

When $i_1 = i_2$, the point A is at earth potential. If the anode load is Z_A and the voltage on the control grid is e, then

$$i_1 = eg_mZ_A/Z_1$$

$$i_2 = e/Z_2$$

and

$$g_mZa = Z_1/Z_2 = S \quad . \quad . \quad . \quad . \quad . \quad (16)$$

The actual measurement of interface resistance is made by injecting a low-level signal at 10^7 c/s and adjusting g_m until $i_1 = i_2$ (indicated by a null balance on the detector output meter). The high-frequency signal is then replaced by one of similar level at 10^4 c/s and, with the same setting of g_m, the resistance R_X is varied to restore the null balance. Under both conditions the circuit gain is given by the ratio Z_1/Z_2 and the additional anode load required at low frequency is read directly from the calibrated resistor R_X.

The interface resistance is then given by

$$\left.\begin{aligned} R &= R_XZ_2/Z_1 \quad \text{for a triode} \\ \text{or} \quad R &= R_XZ_2/Z_1\alpha \quad \text{for a pentode} \end{aligned}\right\} \quad . \quad . \quad . \quad (17)$$

The circuit is capable of detecting resistance changes of less than 0·1 ohm. No measurements of interface capacitance at very low resistance values have been made so far, and consequently the absolute accuracy of the measuring set under these conditions has not been established.

(3.4) Nature of the Interface

The manner in which the interface resistance varies with temperature has been investigated, and the results are shown in curve EF of Fig. 10. The nature of this temperature dependence is similar to that of semi-conductors.* The interface will therefore require activation by an excess component, and the one that obviously comes to mind is barium. The interface may be subject to de-activation by gas poisoning in a manner analogous to that of the barium-strontium-oxide matrix itself.

(3.5) Other Forms of Matrix-Core Failure

Two other forms of interface failure are known, but these are probably of minor technical importance. The first has been described by Raudorf and shows itself as a mechanical loosening of the matrix-core bond. The second form is commonly known as cathode blistering and is usually ascribed to inadequate pre-processing of the cathode core.

(4) CATHODE LOSS BY EVAPORATION

Cathodes work at a temperature of about 1 050° K, and the oxide matrix is therefore subject to thermal evaporation. Two cases must be considered, namely evaporation of the barium-strontium-oxide matrix as molecules of barium oxide and strontium oxide, and evaporation of the barium and strontium metals which are the essential activators of the matrix.

Claassen and Veenemans[22] have measured the evaporation rates of the oxides of barium, strontium and calcium. They find that the relative rates are in the ascribed order and that they follow the usual exponential increase with temperature. Some data extracted from their work are set out in Table 4, which shows that, at 1 000° K, a typical cathode bearing 3 mg of oxide will still retain the bulk of the matrix after a million hours of work. It is clear from these figures that bulk loss of barium-oxide molecules by straight evaporation is not of serious moment at 1 000° K (i.e. the temperature at which the 6P4 is normally run).

Table 4

Temperature	Evaporated quantity	Time for evaporation of 1 mg/cm²
Degrees K	mg/cm²/h	h
1 100	8×10^{-5}	12 500
1 000	$1{\cdot}25 \times 10^{-6}$	800 000

Bulk loss by evaporation of barium and strontium may be more serious, and the phenomenon has been well illustrated by the following simple experiment: Two batches of experimental tubes were prepared; one had cathode cores of nickel, bearing magnesium and silicon as reducing agents, and the other had cores of spectroscopically pure nickel. The tubes of both batches contained only a cathode and a fine open-mesh grid to act as anode, free evaporation from cathode on to the glass envelope therefore being possible. Both batches were run at a cathode temperature of 1 250° K. After 10 h the first batch with reducing cores had developed an intense black deposit of barium and strontium metals on the glass envelope, whereas the second batch, with pure nickel cores, developed no stain after 20 h.

It is concluded from this experiment that a barium-strontium-oxide matrix supported on a core carrying reducing agents may lose that proportion of its weight which is chemically equivalent to the total weight of effective reducing agents in the core. Calculation shows that 10–20% of the useful matrix might be lost in this way with core nickels commonly used in industry.

Eisenstein[23] has examined the reduction phenomenon on similar lines and arrives at similar conclusions.

(5) POSSIBILITY OF THE FORMATION OF NON-EMITTING PATCHES ON THE CATHODE SURFACE

It was suggested earlier in the paper that further work on short-life valves might disclose manners of failure other than those due to normal emission deterioration and interface feedback. One such possibility will be mentioned here to indicate the potentialities of further research.

Efforts are being made at the Post Office Research Station to measure the relative magnitudes of the poisoning effects of various gases on the oxide cathode. During the progress of this work it has been observed that a gas, derived either directly

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* It has since been confirmed by X-ray examination that the interface layers consist of barium orthosilicate. The authors wish to express their appreciation to Dr. Rooksby for supplying this information.

or indirectly from the heated glass envelope of a valve, is more destructive in action than any of the normal gases so far examined (oxygen, chlorine, carbon dioxide, hydrogen sulphide, sulphur dioxide, sulphur trioxide, etc.). Two tentative hypotheses are being examined to explain the phenomenon.

First, it is imagined that the pernicious gas is water vapour. Such vapour may be shown to react with a cathode at 1 000° K in a manner highly detrimental to electron emission. The action appears to be a hydration process followed by fusion or sintering, and cathodes subjected to such action have appeared glazed when viewed under a microscope.

The second hypothesis is more complex, but it also requires the evolution of water vapour from the glass envelope. This water vapour is thought to react with certain metallic carbides in the valve, thereby producing unsaturated hydrocarbons of the acetylene type. These hydrocarbons dissociate on the cathode surface to form non-emitting carbon patches which are stable at the normal working temperature of the valve.

These ideas are clearly speculative at present, but there is much circumstantial evidence to support them. It is, for example, a common experience to note a strong odour similar to that of acetylene after opening a valve to the atmosphere, and mass-spectrograph studies usually report the C_2H^+ ion as a component of valve residual gases.

Work at the Post Office Research Station has concentrated on finding sources of the C_2H^+ ion, and it has met with some small success. There appear to be three possible sources, namely the glass envelope under heat treatment, the barium getter under the action of water vapour, and the oxide cathode itself under the action of water vapour.

The subject of surface patching will be left at this stage, for it is too immature yet to warrant the expression of any opinion as to its importance, and it has been quoted only to illustrate the potentialities of further work on cathode life.

(6) CONCLUSIONS

It is concluded that most present-day valves fail from functional causes, from gross emission deterioration due to gas attack, or from the growth of excessive interface feedback. If these phenomena are avoided by greater skill in mechanical design, by adequate gas scavenging and by use of a cathode core capable of producing no interface resistance, then the authors consider that the life of the valve is probably limited only by evaporation of the activated oxide.

(7) ACKNOWLEDGMENTS

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[The discussion on the above paper will be found overleaf.]

DISCUSSION BEFORE THE RADIO SECTION, 14TH NOVEMBER, 1951

Dr. L. F. Broadway: In Fig. 3 of the paper we have a gas integral which shows on a large scale what is happening over the first few hours of the life of the valve. It would be very interesting to know roughly how much gas the integral represents as compared with, for example, the total integral up to 3 000 or 4 000 hours and whether the amount of gas present at the end of this period of operation of the valve has any noticeable effect on the condition of the cathode during its subsequent life.

On the question of specific deleterious materials, some workers have maintained that chlorine, for example, exercises quite a serious specific effect on the oxide cathode. It has been confirmed, I think, by work on cathode-ray tubes, that chlorine is present in quite unsuspected quantities. According to some unpublished work, some years ago it was discovered that, in baking cathode-ray tubes, quantities of chlorine corresponding to some hundreds of microgrammes could be liberated from the glass bulb. The glass bulb of a cathode-ray tube is certainly very much larger than that of a valve, but there are fairly recent reports from Holland to the effect that they have also found in their valves a serious effect specific to chlorine on the de-activation of the cathode. It would be interesting to hear whether the authors have any evidence on the matter and could tell us whether any of the other gases which might remain have a similar specific effect.

There is one minor point I should like to raise concerning the question of the measurement of the saturation current at an anode voltage of 5 volts—namely, is the interface resistance, in fact, likely to have any effect on the measurement and will the anode voltage applied be sufficient to give a saturation current, having regard to the fact that it is possible that a serious interface resistance has grown up?

Mr. C. W. Cosgrove: Although the authors will be aware of the manufacture of long-life repeater valves carried on for the last 30 years by at least two British manufacturers, they do not mention the fact, and readers of their paper may assume that the possibility of valves giving lives of 40 000 hours and more is projected for the first time as a result of the work described. It is appropriate therefore to consider what were the circumstances leading to the work described by the authors.

During the 1930's, designers of repeater equipment, who had thus far used only triode repeater valves, began to make use of radio frequencies for multi-channel communications, and felt the need for indirectly-heated screened-pentode valves of much higher slope. A few types of high-frequency pentode were developed using the special methods of manufacture established for repeater valves, and these proved satisfactory. With the advent of the 1939–45 War, however, the Post Office were persuaded to use valves which originated for the domestic market, since the labour required to manufacture such valves was so very much less.

After the war the Post Office had acquired the habit of using mass-produced valve types and there was little or no incentive to manufacturers to develop repeater versions of them. The subsequent experience in the operation of Post Office circuits was one factor leading to the initiation of the research work described by the authors.

With reference to Section 2.1.5, the authors state that the traces of residual gas are driven into the cathode. Can they produce evidence to support this statement and to show that the getter does not absorb a substantial part of this gas residue?

In Section 2.2.1, it is indicated that, in the measurement of total emission at very low cathode temperature, "a few hours" must be allowed for the emission to reach equilibrium. Could the authors be more specific on the time required, and would they give their opinion on the nuisance value of a measurement which takes so long a time?

When discussing the results of tests in Section 2.2.2, the authors disclose the fact that certain CV1065(A) valves have been observed to have a life of 60 000 hours, and they appear to infer that the valves now tested will give a similar result. Is this confidence due to the fact (not disclosed) that the CV1065(A) valves now tested are from the same production batch as those which have survived 60 000 hours? If so, the Post Office must have good stocks of old CV1065(A) valves, bearing in mind that 60 000 hours represents nearly eight years of continuous operation. If, however, they base their expectation on the tests now made, then why not conclude that the 6P4 and 6Te4B valves will do even better in view of their better performance as shown by Fig. 5?

Dr. L. E. Ryall: The emitting properties of a cathode are now known to be affected by its surface state, which involves both physical and chemical problems, together with properties of the bulk material in which conduction through the cathode, electrolysis and the movement of barium to the surface all play their parts. In addition, the growth of an electrical interface resistance between the cathode and the core also affects the emission properties. Because there has been a lack of understanding of the factors that control the cathode emission during life, valve manufacture has to some extent become an art, and processes have been adopted that have little scientific justification. Since there are so many factors that can affect cathode emission during life, any study of these factors must be made with as complete a control as possible of the materials and techniques employed in the manufacture of the thermionic valves under investigation. To this end the authors have built their own pumps, avoiding any rubber connections, which will maintain a manifold pressure of less than 10^{-7} mm Hg. They have also developed an ionization gauge which, by avoiding the effects of X-rays, will measure pressures 100 times less than existing commercial ionization gauges. Thus, for example, by careful control of their experiments, they have been able to show that the growth of interface resistance can be seriously affected by the type of heater material used—a result that was quite unexpected.

In Table 3, the calculated value of the interface resistance is based on the assumption that the latter accounts for the whole of the reduction in mutual conductance by the negative-feedback effect it produces. In general this is not the case. We know that the interface resistance grows much more rapidly as the cathode temperature rises, and since the centre of the cathode is hotter than the ends, the interface resistance is greater in the middle than at the ends of the cathode. This produces a non-uniform emission along the cathode surface and a reduction in the mutual conductance of the valve which is additional to that due directly to the mean interface resistance. Thus the calculated value of this resistance is, in general, greater than the measured value. Because the interface resistance is not uniform along the cathode its effects can be simulated only by a more complex network than a simple resistor in parallel with a capacitor.

I think the authors' estimated possible saving of heater power of 25% is unduly conservative. They have already produced valves having the same initial total emission as commercial valves with a saving of 50% heater power, but since these valves do not lose their emission appreciably during life, it may well prove to be unnecessary to use even 50% of present heater power if the laboratory techniques can be converted to commercial practice. The valve will take longer to warm up, but for many applications where it is running continuously this is unimportant.

The growth in the use of thermionic valves is retarded and limited at present because they have not an indefinite life. Their applications in industry where no skilled maintenance is available would be vastly increased if one could "fit and forget" and would, I am sure, result in an increase in valve production, despite the loss of the replacement market.

Mr. J. Bell: Section 1.5 of the paper classifies valve failures into two categories, namely "functional" and "cathode." That subdivision may be suitable for the needs of the present paper, but for general use I think that a different sort of classification is to be preferred, and I should like to hear the authors' comments on this. I like to use a system whereby failures are divided into two rather different categories, one to include the catastrophic failures, i.e. those which happen suddenly and cause complete breakdown of equipment, and another to embrace the characteristic failures which, like cathode failures, normally happen slowly and result in a gradual deterioration in the performance of equipment rather than sudden breakdown.

My general comments concern the impact of work such as this on the life of modern mass-produced receiving valves. I should like to approach this through the conclusions in Section 6 which state that if the causes of failure of present-day valves are avoided by greater skill in mechanical design, by adequate gas scavenging and by the use of a cathode core capable of producing no interface resistance, then the authors consider that the life of the valve is probably limited only by evaporation of the activated oxide.

I want to suppose that we have the necessary skill in mechanical design, that we know how to remove the gas, and also that we have suitable cathode core materials. I think that all these things are at hand. Why is it, then, that we do not make valves the life of which is limited only by evaporation of the cathode material? I think the answer is that we do sometimes do so, and this point is illustrated in the paper. We are given examples of the large variation in life performance which can occur between batches of the same type of valve made at different times by the same manufacturer. The authors do not suggest that this sort of thing can be put right simply by using a cathode core which produces no interface resistance, but I suggest that very much more than this is necessary. I believe that the large spread in life performance is very largely due to lack of sufficient control of raw materials and processes throughout a very complex manufacturing procedure, and I think that before full advantage can be taken of advances in specialized techniques, very serious attention needs to be given to the problem of getting everything absolutely right simultaneously, all the time.

Dr. Hilary Moss: The paper faces squarely, perhaps for the first time in published work, the great issue of whether the classical methods of valve life testing are not rather futile. I think that every valve maker must have been worried, perhaps rather secretively, by the tremendous deviations which are observed between valves on life test which have nominally been processed in the same way.

If the conclusions of the authors in systematizing this most complex subject stand up to the hard test of experience, then the paper will rank as a corner stone in the history of this subject. There are, however, a number of assumptions made which will need justification by larger-scale experience before final conclusions on the validity of this work can be whole-heartedly accepted.

Apart from the interface problem, which I am not going to discuss, the paper raises two fundamental assumptions which I think might have been emphasized a little more fully. The first assumption is that $\int_0^\infty kdt$ is a unique measure of the ultimate performance of the valve on life so far as vacuum questions are concerned. This is certainly implied in the paper, although perhaps not so expressly stated. Surely the authors will agree that this sweeping statement should be modified by the inclusion of a multiplying factor, say $\phi(G)\int kdt$ where $\phi(G)$ is some undetermined function of the nature of the gases present. I am sure the authors will agree that the behaviour of valves having equal $\int kdt$, one integral being due to, say, a halogen and the other to, say, hydrogen, would be markedly difficult, since these reagents have remarkably different effects on oxide cathodes.

The second fundamental assumption in the paper is that deductions can be made about the behaviour of the cathode when it is operated at far below its normal temperature. We must all agree with the unsatisfactory nature of pulse tests, which seem the only alternative, but that, of course, does not necessarily justify the author's method. Such correlation as exists is, at the moment, entirely experimental and seems to me somewhat at variance with what one would expect on theoretical grounds where ionic mobility, at least in the classical theories, plays a vital part.

Dr. Ryall has suggested that valve makers may be able to produce valves with cathode dissipation about one-half of average present-day value. This conclusion would seem to have some justification from the authors' work, so far as laboratory produced samples are concerned. However, we must not confuse what is possible under laboratory conditions with that under mass-production conditions. These are very different issues and a great deal of water may have to flow under the bridge before valve makers will be consistently able to bring about the improvements which the paper suggests may be possible.

Mr. C. H. Foulkes: It has already been mentioned that in the Conclusions the word "if" appears, the "if" implying special conditions. I have been interested for a long time in valves made under special conditions, namely the so-called repeater valves which have evolved over the last 30 years. These have been designed and processed to give long and reliable life and I find that they have succeeded on the whole even when the cathodes have had to work under conditions where the voltage would vary over very wide limits.

One very important factor has been mentioned during this discussion and that is that the life of the valve is lengthened if the cathode temperature is reduced to the minimum permissible value, the reason being that the growth of interface resistance is delayed. With modern telecommunication equipments in which the heater voltage can be kept within precise limits, the cathodes can now be operated at much lower average temperatures than was possible in the past. In one particular case the introduction of close tolerances of heating supplies has enabled the nominal heater voltage to be dropped by 10%, and the life has been increased from 10 000 hours to more than 30 000 hours.

However, it is not simply a question of taking a valve and redesigning the heater to operate at a lower temperature. At low temperatures cathodes are very susceptible to poisoning and a whole new and more tightly controlled processing art has to be developed if one is going to obtain a reasonable yield of valves to work at this low temperature. When these precautions have been taken it is possible to make valves with very long average lives. In fact, such valves are in regular production.

The effect of the build-up of interface resistance is far more noticeable in high-slope valves, but the essential factor is the slope per unit area of cathode. In some valves where very strict capacitance requirements have to be met, it is necessary that the slope per unit area should be very high, but there is another class of valve which has been designed for use in submerged repeaters where lives of the order of 10 to 20 years are aimed at, in which not only is the cathode temperature kept extremely low but also, as a further aid to extending the life, the slope per unit area of cathode is kept down.

With regard to interface build-up and gas poisoning, it is not my experience that gas poisoning is the cause of poor life—I have been associated with valves which have been more or less specially made, and I find that the trouble is interface resistance. It is a little tantalizing, in some respects, that I have found—rather contrary to what the authors have found—that if I take a batch of valves for long-term life test there is the odd valve in which the interface resistance does not start to build up until well after the others in the batch. It is tantalizing because it seems that the answer is so near at hand but that we have not yet put our finger on it. I hope the authors will help us to do that.

Mr. T. J. Jones: It is clear that improvement of vacuum must have a beneficial effect on valve life. In fact, I believe that the improvement of vacuum that has resulted from the use of barium instead of magnesium as the standard getter material has been responsible for most of the improvement that has taken place in the quality of thermionic cathodes in recent years. It is also clear that it is essential to ensure that the resistance of the cathode coating (including that of any interface layer that may be present in the coating) does not increase appreciably as the valve is used. Experiments appear to indicate that the thermionic activity of a cathode will remain high and the resistance of the coating will remain low as long as there are sufficient free barium atoms dispersed through the coating. Therefore, anything—such as an improvement of the vacuum, or a reduction of the operating temperature of the cathode—which will help to conserve the free barium content of the coating will thereby help to keep the cathode activity high and the coating resistance low.

It appears that the vacuum-factor characteristics in Figs. 2 and 3 refer to "aged" valves, and that no account was taken of the ion currents that reached the cathodes during the ageing process. During ageing there is usually a large ion current to the cathode, and it seems to me that the contribution of this current to the gas integral should have been taken into account.

In the low-temperature-emission measurements which are described in Section 2.2.1, it is assumed that, if the heater power is kept constant for all the measurements on a particular valve, the temperature of the cathode will remain the same for all the measurements. This assumption presupposes that the thermal emissivity of the cathode does not change during cathode life. However, the physical properties of the core surface and of the coating may change appreciably during valve life and, consequently, the thermal emissivity of the cathode may also change. Thus, it is possible that some of the observed emission changes were caused by changes in the testing temperature rather than by changes in cathode activity. In this connection, it should be remembered that the percentage change in thermionic emission which results from a given change in cathode temperature is considerably greater at the low testing temperature than it is at the higher operating temperature.

The thermionic activity of an oxide cathode and the electrical conductivity of its coating depend primarily on the density of free barium atoms in the coating. Therefore, during the operation of a valve, the cathode activity and conductivity will remain at about their original values only for as long as the original amount of free barium in the coating is maintained. However, even in the best possible vacuum, residual gas and evaporation will tend to diminish the number of free barium atoms in the coating. Hence, to maintain the free-barium concentration there will have to be a mechanism in the cathode which will continue to liberate barium to replace the lost atoms. The paper is concerned mainly with means of conserving the free-barium content of a cathode. In my opinion, it is equally important to consider the factors which are responsible for replacing the barium atoms that are unavoidably lost during the operation of the cathode. If these factors fail to produce the required free barium the emission will fail even though the vacuum is satisfactory and the cathode remains well coated. Cathodes which appear to have failed because of failure of the barium-replenishing mechanism are often encountered.

Mr. C. C. Eaglesfield: In an aged cathode there are at least three impedances in series, namely the vacuum gap, the bulk resistance of the coating, and the interface resistance. To distinguish between these three is difficult. Since the contact-potential method described has limitations, the method I have used for measuring the total resistance may be of interest. This is to measure the shift in the grid-voltage/grid-current characteristic when cathode current is caused to flow by an anode voltage. Measurements made on aged valves show that the cathode resistance at $V_h = 2$ is sometimes very high—up to 50 000 ohms—so that 5 volts on the grid would not cause saturation. The interface resistance sometimes outweighs the bulk resistance at $V_h = 2$ volts.

At the working heater voltage the interface resistance always completely outweighs the bulk resistance, and as bulk resistance and emission go together, it would seem that the interface resistance outweighs the emission, which indeed is my experience.

I have tested many valves and always, unless they were very gassy during life, any deterioration was due to interface resistance.

I am therefore interested in the authors' Conclusions, in which they put gas attack in front of interface resistance as a cause of failure. In the paper, the main evidence is in Fig. 5, which shows the decay of low-temperature emission up to 3 000 hours, but the worst case shows 10% emission remaining. That would mean no change in the working characteristics, so Fig. 5 shows no important emission decay, and one can hardly extrapolate to guess the emission after longer periods. It is stated that the batch showing the lowest emission—i.e. 10% or rather more—had a high probability of failure before 6 000 hours, but it is not said explicitly that the cause was low emission. I should like, therefore, to ask the authors whether this batch at failure had an emission low enough to explain their failure (that is, about 0·2% of their initial emission), whether the valves showed significant gas current during life, and whether they were tested for interface resistance.

In anticipation of their reply that the valves were not gassy during life and did in fact die of emission decay, the suggestion will probably be that the emission was damaged in early life by a high gas integral. This conception of damage ceasing after the very early life of the valve, but causing failure perhaps a year later, is certainly interesting. But perhaps a more acceptable explanation is that the valves might have had a virulent contamination which gradually poisoned the cathodes. But such a process is hardly typical, neither is it what is usually considered as gas attack.

Dr. J. R. Tillman: A study of interchannel interference in time-division-multiplex telephony has produced sensitive techniques for the measurement of the transient response of some electronic devices, particularly the oxide-coated cathode.

Thus, using a time scale of the order of 1 millisec, it was found* that the cathode current of a valve, operated conventionally, remembered a pulse of current of a few milliamperes occurring earlier, by being greater or less than its expected value by an amount proportional to the size of the pulse. The memory decayed with a time-constant of about 1 millisec. A valve whose cathode was in good condition remembered a positive-going pulse by passing, subsequently, more current; one with a poor cathode remembered by passing less. By a suitable combination

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* TILLMAN, J. R.: "Space Current Changes in Thermionic Valves following Small Pulses of Current," *Proceedings of the Physical Society, B*, 1951, 64, p. 1046.

of electrode potentials for a few seconds or minutes, involving a release of gas or other poisoning agent, the sign of the memory of a good valve could be changed temporarily. Do the authors see any use for this technique as a test of the state of a cathode? It has advantages over total-emission tests in demanding neither heavy pulses of current nor a much reduced cathode temperature.

We then turned to measurements on a time scale of microseconds, comparable with the product *RC* of the parallel resistance-capacitance combination used to represent the interface impedance of a valve. Eisenstein's recent work,* using the transient response to deduce the interface impedance, depended on measurements taken from traces on the face of cathode-ray tubes, and it dealt primarily with valves having large values of *R* (about 200 ohms); finer points may well have been missed.

R and *C* were first measured with a circuit similar in form to that of the authors' Fig. 12, but differing in some important parameters and more easily capable of high accuracy, e.g. better than ± 1% for *R* and ± 5% for *C* when the valve under test, though new and showing no interface impedance, had a known parallel *RC* combination placed in its cathode circuit to simulate an interface impedance. The impulse response of the new valve with its added cathode impedance had the correct overshoot, decaying exponentially with the expected time-constant. The decay of overshoot from an aged valve known to have interface impedance and without any added components was, however, not exponential, and departed considerably from that calculated from a knowledge of the interface resistance and the supposedly single accompanying capacitance. The non-exponential decay could, however, be simulated by more complex resistance-capacitance networks in the cathode circuits of two or more valves otherwise connected in parallel.

There are reasons for dismissing the possibility that the non-exponential decay is due to either *R* or *C* of the simplest representation changing sufficiently rapidly. It seems more likely—bearing in mind the non-uniform emission over the cathode area and the resistance of the coating along its length (perhaps hundreds of ohms per pitch of the grid wires)—that it is evidence of unequal growth of interface impedance, possibly as many small patches. Have the authors any direct physical evidence of patchiness?

Mr. A. H. Beck: At the laboratories with which I am associated we have carried out some studies on interface resistance which parallel rather closely those of the authors. Our findings are slightly different. The first point which is worth noticing is that we find that the current passed through the interface has a very marked effect on the rate of build-up and on the general behaviour of the cathode. I ought to say that we have done much of our work using techniques suggested by Waymouth† and Eisenstein,‡ in which the valve is run with zero current for about 1 000 hours at a high heater voltage, so that the interface, if any, builds up rather fast. That is an important practical consideration, because it makes it possible to get a test on interface in 1 000 hours, instead of having to wait for about 6 000 hours.

When we draw a constant current from such a cathode, the interface resistance runs down in a period of several minutes from an initial value, which may exceed 100 ohms/cm^2, to a much lower value, 30–40 ohms/cm^2, and we find that the rate of activation of the interface resistance depends on the quantity of electricity passed through it as well as on the current. In particular, we find that for currents or less than about 30 mA/cm^2 there is substantially no reactivation of the interface layer, and when we get to currents of the order of 200 mA/cm^2 the interface practically disappears in a very short time. It is then possible to de-activate the interface by running it again with zero current and repeat the whole process, and so make an extensive study in a relatively short space of time.

In our opinion, this indicates that, even in well-aged cathodes of this sort, electrolytic phenomena must play quite a major role, but it seems from the literature that most other authors think that electrolytic processes end rather suddenly after the initial ageing. We agree that there is great divergence in behaviour between one cathode and another, even when great care is taken to make the valves in a batch by identical methods and when processing has been closely controlled. We are sorry that we cannot endorse the American view that, if the silicon content in the sleeve is cut down to a sufficiently low level, zero interface build-up is obtained. On that point I should like to ask the authors where the silicon comes from, because it appears in valves, even when there is certainly no silicon in the sleeve.

I should like to ask the authors whether, in the preparation and manufacture of their valves, they really do anything that is not done in the normal manufacture of a long-life repeater tube?

I should like to know, as a last point, whether it is the opinion of the Post Office group that the cathode really behaves as an excess semi-conductor in the operating temperature range, or do they think that the theory of Loosjes and Vink* is more applicable? Or, as a last possibility, do they agree with Mr. Wright† when he suggests that there are two distinct classifications of oxide cathode, but that we do not know when we are going to get cathodes of one type or the other?

Mr. D. A. Wright: We have some evidence that the performance of a valve can deteriorate under conditions where there is no growth of interface resistance. This is contrary to the experience of a previous speaker, and it would be of interest to have the authors' comments. We notice, for example, valves on life test where there is a decrease in the slope accompanied by a decrease in emission. The latter is however by no means sufficient to be the direct cause of the former.

Depression of characteristics can be caused not only by growth of interface resistance, but also by an increase in coating bulk resistance, or by the formation of deposits on the electrodes. These deposits may either decompose on bombardment, reducing the emission of the cathode in operation, as distinct from that measured in a reduced test, or they may modify the characteristics by changing the physical dimensions of the grids. The last of these effects can be particularly serious. The first is due to too much residual gas in the valve. This gas enters the coating, causing the increase in resistance and a corresponding decrease in emission.

As regards coating resistance, we have tried to use the retarding-field method described by the authors, but invariably we have found that the estimated value of resistance varies widely with the current density at which the voltage intercept is measured. This may be genuine, indicating a non-linear resistance, but it may, on the other hand, be due to work-function variations or reflection effects, either of which would invalidate the method.

Mr. Cosgrove referred to the long time required using the low-temperature method for emission measurement. We have regularly relied on pulsed emission measurements, and do not consider that they impair the emission. What is the present view of the authors?

Reference has been made to the possibility of obtaining good valve performance with cathodes at greatly reduced temperature. While this should be feasible at low current-density if the vacuum conditions are very good, difficulties will be encountered at higher

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* EISENSTEIN, A.: "The Leaky-Condenser Oxide Cathode Interface," *British Journal of Applied Physics*, 1951, 22, p. 138.

† *British Journal of Applied Physics*, 1951, 22, p. 80.

‡ *Ibid.*, 1951, 22, p. 138.

* Phillips Research Reports, 1949, 4, p. 449.

† WRIGHT, D. A.: "Electrical Conductivity of Oxide Cathode Coatings," *British Journal of Applied Physics*, 1950, 1, p. 150.

current-densities owing to I^2R heating, since the coating resistance rises as temperature falls. This will be troublesome even if uniform, but coating heating of this type is often localized, and leads to marked instability of operation.

Our observations of localized coating heating are relevant to a question by an earlier speaker. We consider that coatings and core-coating bonds are not homogeneous, that the interface resistance is partly as visualized by Raudorf, and that it is not solely due to the layer which can be detected chemically.

With regard to ionic conductivity, our observations are that the life of a coating at high current-density is considerably longer than would be predicted from Isensee's figures. Thus the ionic conductivity must be less than Isensee's value during the greater part of the valve life.

Mr. H. Williams: I think that it is likely that our requirements of submarine repeaters actually started up some of this work.

Taking the design requirements first, I think that the three main things which we should like are, first, a range of valves to the same specification and the same basis, preferably from a number of manufacturers. Secondly, the economics of modern transmission systems are obtained, at any rate so far as the terminal equipment is concerned, by complicated circuits and in general, numbers of valves. This brings in the question of the heating in the building at the ends of the system, and anything that can be done to reduce the temperature of the equipment will be thankfully received. The modern tendency seems to be to reduce the size of the envelope, which means closer packing and tends to make the equipment hotter still. I do not think that these conditions are conducive to long life. Thirdly, we should like to know whether the filament should be operated at a constant voltage, a constant current or a constant power.

Coming now to maintenance, I should not like to pretend that the valve is the only difficulty, although it is certainly a major one. There are other components which give us just as much trouble. Here again, however, modern systems put a large number of channels through one valve, and this really means that our valves should last much longer than before, when only one channel was carried by a valve. We are therefore looking for something much better than before. The relatively short lives which we get increase the annual charges not only because of the replacements but also because we have to employ complicated circuits to change from one equipment to another when a failure occurs, and this means that, in some cases, we have to double the amount of equipment in the station.

Referring to Section 1.5, I do not know whether it is possible, but it seems to me that there is need to standardize some criterion of when a valve has failed. In my laboratory, when one of the major parameters changes by 30% and 50% of the batch has failed we regard these as the criteria; but other people use other figures.

Several speakers have mentioned the long lives obtained from our old repeater valves. I looked up some figures this afternoon, and one of the valves which I picked on was the VT81 (CV1659), which was a repeater valve, for which the average life was 5 000 hours. For the VT149, which I do not think was a repeater valve, I find that the mean life was about 30 000 hours. For the CV1699, again not a repeater valve, I found that, according to the records, the mean life was 20 000 hours, and about 12% failed in the first 1 000 hours. This seems to be typical of the inconsistencies which exist in the subject at the present time.

So far as submarine repeaters are concerned, I should like to emphasize one point. If we are going to consider a long system, we must have a mean valve life of at least 100 000 hours, and, what is more, the standard deviation must be very small. This is allowing for such safeguards as can be introduced—double amplifiers and so on. Perhaps the authors can say whether this requirement is likely to be met in the future.

Fig. 5, and the results which we have found in our own laboratory, show that in some cases valves actually improve as they get older. Can the authors tell us why?

Mr. A. A. Robinson: Fig. 6 shows that, in the case of the CV1065, g_m remains practically constant until almost the end of valve life. Is this a property of valves in general? If so, designers can assume that g_m will remain constant during nearly the whole of the useful life.

The authors mentioned that in the case of the CV138 an interface resistance of 60 ohms would often make the valve unusable. This is not so in many non-linear circuits and circuits with negative feedback, where the designer can allow for the growth of interface resistance, provided that he can assume that the resistance will never exceed a fixed value which is not too high.

The authors point out that one of the factors which encouraged their research was the need for valves for use in equipments employing large numbers of valves. Electronic computers are an example of such equipment, and it may not be irrelevant if I mention some figures relating to the computer at Manchester University. This equipment contains 4 000 valves, and it has now run for about 1 000 hours since it was put into service in July, 1951. In that time 43 valves have failed, including 18 functional failures, 14 cathode failures, and 11 failures where the cause has not been recorded. This corresponds to 93 000 valve hours per failure. It would, however, be unfair to deduce an average valve life of 93 000 hours from these figures, since they refer to the early life of the valves.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Drs. G. H. Metson and **S. Wagener** and **Messrs. M. F. Holmes** and **M. R. Child** (*in reply*): We are grateful for the extensive range of penetrating questions that have arisen in the discussion. It will be appreciated that the paper was prepared from material available to us some two years ago and our further efforts since that time have left us in more sophisticated mind on some aspects of this undeniably complicated subject. In general, however, we have increased our confidence in the main conclusions of the paper, namely that common cathode failure is an admixture of two superimposed deleterious actions—gas attack and interface-resistance growth. The relative intensity of the two forms varies from valve batch to valve batch, and where one form predominates it requires sensitive forms of analysis to detect the other. We regard both forms as major contributory factors in the failure of common receiving valves.

Before replying to the questions we should like to comment on a point raised by Mr. Williams concerning the possibility of very long life (100 000 hours or more) in valves. So far we have experienced no causes of common cathode failure which cannot be ascribed to gas attack or interface-resistance growth and are therefore inclined to conclude that the basic limiting factor in life is evaporation of the active matrix. This factor will probably set the cathode in the 100 000-hour class for life at conventional operating temperatures.

Considerations of Residual Gas.

Drs. Broadway and Moss and Mr. Jones raised questions concerning the correlation of a high gas-integral and short valve-life. We have come to realize during the past two years that our conclusions were over-simplified for two reasons. First, the nature of the gas is of crucial importance; e.g. if the high integral is due to hydrogen gas then the cathode will suffer no damage.

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The second weakness of the integral as an indicator of probable life is its insensitivity as a pressure detector due to X-ray irradiation. The CV138, for example, shows a residual-vacuum factor at about 1×10^{-7} mm Hg, and pressures below this will not be observable. A pressure of 1×10^{-8} mm Hg of oxygen maintained for a few hundred hours may well be ruinous to the cathode. In general we would now say that a high gas-integral should be regarded with suspicion by the production engineer.

Dr. Broadway raises the question of toxicity of chlorine in valves. We have made relative-toxicity tests on cathodes of a range of the common molecular gases and find that oxygen is the worst, chlorine being only about one-fifth as toxic as oxygen. These tests refer to relative quantities of gases at constant pressure (1×10^{-5} mm Hg) to effect a 90% irreversible reduction of total emission in well-activated laboratory cathodes.

In reply to Mr. Cosgrave, evidence that residual gas is driven into the cathode during life is supplied by resistance measurements of the oxide coating. These show that the resistance in valves with high vacuum-factors may rise from its initial value of 1 to 2·5 ohms/cm² to as much as 15 to 20 ohms/cm² during life, which is obviously due to gas being taken up by the coating.

Interface-Resistance Phenomena.

In reply to Mr. Foulkes, we confirm that when we investigated numbers of valves prepared in the same way, a very wide spread between the interface resistances of individual cathodes was observed. The causes of this spread are being investigated and some influencing factors—for instance the state of heaters, mentioned by Dr. Ryall—have been discovered.

We are very interested in Dr. Tillman's work and agree that the interface resistance may not be uniform; so far, however, we have no direct proof of patchiness.

We are in agreement with Mr. Beck concerning the effect of current on interface resistance; we also employ the zero-current technique for special investigations. Contrary to Mr. Beck's observations we have found that the silicon content of the cathode sleeves is of importance. So far, no interface resistances have been measured with silicon-free sleeves. Possibly the different results obtained by Mr. Beck could be explained by the mechanical loosening of the matrix-core bond as suggested by Raudorf.

Thermionic Emission and Conductivity.

We disagree with Dr. Moss in his opinion that there is only an empirical relationship between the low-temperature total emission and the cathode state under normal conditions. We consider that the low-temperature emission level is a measure of the instantaneous emission at normal temperatures, as determined by the particular conditions of ionic mobility and concentration existing at the moment of measurement. It has now been shown that a few hours are not required for the measurement and satisfactory results have been obtained in five minutes or less.

It is our view that pulse-emission measurements do not impair the emission provided that the valve is free from gas and has a clean collector. If these conditions do not obtain, severe deterioration has been shown to occur during the measurement. Such deterioration is not, however, usually permanent, and complete recovery to the same or higher level generally occurs after a period of normal running.

We do not believe that there is any marked change in thermal emissivity during the first few thousand hours of life, nor do we believe that either interface resistance or bulk resistance significantly affects the measured emission at low temperatures.

The retarding-field method of determining coating-resistance does, as Mr. Wright points out, give a value of resistance dependent on current. It is believed that such results can indeed derive from the patchy nature of the cathode and that, if they do, the value of the resistance obtained from the knee of the characteristic is a fair approximation for the cathode resistance.

In reply to Mr. Eaglesfield, we do not agree that the interface resistance always outweighs the bulk resistance, nor do we agree that the interface resistance always outweighs the emission. Such statements, in our view, are over-simplified. In answer to the point raised in connection with Fig. 5, the valves in batch (*d*) which failed before 6 000 hours had emission low enough to explain their failure; they also exhibited gas currents and showed negligible interface resistance.

We agree with Mr. Jones that replenishment of excess barium in the oxide coating is an important aspect. We maintain, however, that losses of such barium, which are due either to bad vacuum or to evaporation, can be kept negligibly small and that for this reason replenishment is not absolutely necessary.

The importance of electrolytic phenomena is emphasized by the influence of high current-densities on interface resistance, as mentioned by Mr. Beck. It can be shown, however, that the accepted values of ionic conductivity are adequate to explain the movement of the quantities of excess barium necessary for activation or deactivation of the interface layer. We agree with Mr. Wright that the ionic conductivity might even be lower than the values indicated in the literature, which are close to the sensitivity limit of present methods of measurement.

Concerning the controversy about the various mechanisms of electron conduction in oxide coatings at normal operating temperatures, we think that a decision between these can be made only after further experimental evidence has been obtained.

Miscellaneous.

We agree with Mr. Wright that I^2R heating may well limit low-temperature running conditions. In reply to Mr. Cosgrove, the confidence in the type CV1065(A) derived from Fig. 5 applies only to immunity from gas attack. Similar confidence applies to the 6P4 and the 6Te4B with the same limitation. The stability of g_m in Fig. 6 applies only to valves with high initial emission values. We agree with Mr. Williams that the modern tendency to reduce the size of the envelope is not conducive to long life. We consider that it is immaterial whether the heater is operated at constant voltage, constant current or constant power. The improvement in emission observed in some cases in Fig. 5 is probably due to replacement of surface barium destroyed during manufacture.

We agree wholeheartedly with Mr. Bell in his remarks concerning the necessity for strict control of materials and processes during valve production. We believe that much of the present-day inability to improve or even closely to control quality in valves is due to the movement, or lack of movement, of small quantities of matter in the valve at certain critical times during manufacture. The quantities involved may be so small as to be beyond the limits of present-day measurement, but their consequences may be all too apparent. Such effects can be occasioned by even slight variations from a production plan proved empirically sound.

(2) Douglas, R. W., and James, E. G.: "Crystal Diodes," *Proceedings I.E.E.*, 1951, **98**, Part III, p. 157.

(3) "Improvements in or relating to Holders or Mountings for Circuit Components for Waveguide or Like Structures," British Patent No. 689179.

(4) Collard, J.: "The Enthrakometer; An Instrument for the Measurement of Power in Rectangular Wave Guides," *Journal I.E.E.*, 1946, **93**, Part IIIA, p. 1399.

(5) Collard, J., Nicoll, G. R., and Lines, A. W.: "Discrepancies in the Measurement of Microwave Power at Wavelengths below 3 cm," *Proceedings of the Physical Society*, B, 1950, **63**, Part 3, p. 215.

(6) Pound, R. V.: "Electronic Frequency Stabilization of Microwave Oscillators," *Review of Scientific Instruments*, 1946, **17**, p. 490.

(7) Mumford, W. W.: "A Broad-Band Microwave Noise Source," *Bell System Technical Journal*, 1949, **28**, p. 608.

(8) Dicke, R. H., Beringer, R., Kyhl, R. L., and Vane, A. B.: "Atmospheric Absorption Measurements with a Microwave Radiometer," *Physical Review*, 1946, **70**, p. 340.

DISCUSSION ON "THE LIFE OF OXIDE CATHODES IN MODERN RECEIVING VALVES"[*]

NORTH-EASTERN RADIO AND MEASUREMENTS GROUP, AT NEWCASTLE UPON TYNE, 3RD DECEMBER, 1951

Mr. W. Macrae: While the application of high pulse voltages to a valve in order to draw the saturation current may cause some disturbance of the cathode surface, much useful information can be obtained from such tests, particularly if the current/voltage characteristic can be observed. This can be done conveniently by discharging through the valve a condenser, initially charged to a potential in excess of the saturation voltage, and observing the trace of a cathode-ray tube, the X and Y deflections of which are proportional to the voltage across the valve and the current through it, respectively. The curve traced out for a uniformly activated cathode has a characteristically sharp "knee" at the saturation point, whereas the knee for an unevenly activated cathode is indeterminate.

Similar discrimination can be obtained by measuring the cathode current well below saturation current at normal cathode temperature—say 20–30 mA/cm^2 for 1 000° K—and repeating with a reduced heating power but with the same diode voltage applied. A valve with a well-activated cathode gives a small drop in current, as shown in curve (i) of Fig. A, whereas a poorly activated cathode results in a greater fall such as indicated in curve (ii). The lower-temperature test point is chosen to be slightly above that at which the test current corresponds to the saturation current. For comparison, the position of the still-lower-temperature test point described by the authors is shown in the Figure. The test just described is a convincing one, particularly as the currents involved are of the same order as the normal valve operating current.

Mr. J. C. Finlay: Measurements throughout life tests of mutual conductance alone are clearly misleading. Total-emission and vacuum-factor measurements offer valuable criteria for non-destructive tests, but these in turn must be carefully correlated in order to avoid misinterpretation. The phenomenon of resistive interface growth between core and emitter would appear to justify and explain several other common effects. The advantage has been mentioned of under-running the emitter and also of using a pulsed-current technique rather than complete cut-off standby operation in retarding interface growth and consequent "poisoning." Is the pulse reactivation which has often been successfully tried on emitters also justified on this basis?

Although the paper refers to thermionic valves, have the authors any similar experience and information on the finite life of cold-cathode gas-filled tubes and, in particular, the multi-electrode low-voltage form (the cold-cathode relay tube), which has been widely used for selective ringing, radiation counting and other standby relay applications. The special feature of such tubes is that, in the absence of a heater, the life is dependent simply on the total hours during which current is actually drawn in conjunction with the magnitude of the current, and in standby operation a relatively short total life may correspond to an extremely long effective life. The emitter is of the same type (barium-strontium on nickel) as the conventional thermionic type, and from various tests Rockwood[†] concludes that barium is continually lost by sputtering and replaced at the surface until the reservoir of barium oxide in the cathode coating is depleted. A theoretical equation for the sputtering rate, derived by Townes,[‡]

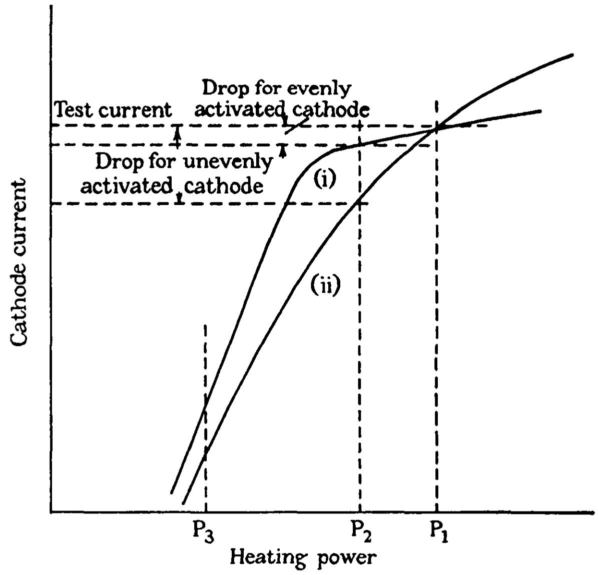

Fig. A.—Cathode current/heater power characteristic at constant diode anode voltage.

P_1 = Normal heater power.
P_2 = 75% heater power.
P_3 = Low-temperature test point for test described by the authors.

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[*] Paper by G. H. Metson, S. Wagener, M. F. Holmes and M. R. Child (see 1952, 99, Part III, p. 69).

[†] Rockwood, G. H.: "Current Rating and Life of Cold-Cathode Tubes," *Transactions of the American I.E.E.*, 1941, 60, p. 901.

[‡] Townes, C. H.: "Theory of Cathode Sputtering in Low-Voltage Glow Discharges," Presented to the American Physical Society, Providence, R.I., June 20th, 1941.

agrees in form very well with practical determination of life at various currents, and an important practical conclusion is that the life decreases very rapidly with increase in current.

Mr. D. H. Thomas: I am much intrigued by the possibility of vintage years in the production of valves by a particular manufacturer. In connection with the method used in Section 2.1.2 for vacuum measurement I have found it far from easy to measure the small reverse grid current in the presence of stray leakage currents, and wonder if this was true in the authors' work. I would also welcome some indication of the value of c in eqn. (2)—it seems to vary over a 1 000 : 1 range from the authors' figures. The authors do not make it clear if life tests were done with anode voltage applied, or with only the heater energized; it seems to me that the presence of the h.t. supply might influence the life. The information that even temporary over-heating can shorten the expectation of life is important; have the authors any comments to make on the claims sometimes made that such treatment can reactivate a worn cathode? Finally, I wonder if changes in the cathode, such as the Raudorf effect, can be detected or evaluated by measurement or analysis of the flicker noise.

Messrs. G. H. Metson, S. Wagener, M. F. Holmes and M. R. Child (*in reply*): We agree with Mr. Macrae that measurements at normal and 75% normal heater power can give a useful indication of the state of the cathode. We have ourselves used a similar test, measuring the mutual conductance g_m at normal and 87% normal heater power, and have obtained a fair correlation between the change in g_m and the low-temperature total emission.

In reply to Mr. Findlay, we can say that the reduction of interface resistance under pulsed conditions (after the cathode has been run in the cut-off condition for a period) has been encountered in work undertaken by J. R. Tillman and H. Yemm. There is, however, evidence that the improvement under pulse treatment is less effective than the application of a direct voltage. We have no information on the life of cold-cathode gas-filled tubes.

We agree with Mr. Thomas that it is difficult to measure small reverse grid currents in the presence of stray leakage currents. It is regretted that the wrong impression was given in the last paragraph of Section 2.1.2. The value of c in eqn. (2) is of the order of 1×10^9 in the units quoted, and should be derived from the figures given for the higher pressure. The vacuum factor of 500 at the lower pressure is the k_0 value and cannot be substituted in eqn. (2).

Typical life-test rack conditions are given in the first paragraph of Section 2.2.2. In all normal life tests the h.t. supply is applied. We agree that overheating the cathode (but not the other electrodes) in the absence of ionizing voltages may, in certain circumstance, reactivate a worn cathode. We have no information on the correlation of the Raudorf effect and flicker noise.

DISCUSSION ON "THE AUTOMATIC MONITORING OF BROADCAST PROGRAMMES"*

NORTH-EASTERN RADIO AND MEASUREMENTS GROUP, AT NEWCASTLE UPON TYNE, 7TH JANUARY, 1952

Mr. J. Hare: In the paper it is stated that the r.m.s. value of the wave would give a more accurate comparison, but because of practical difficulties this is not used; the integrated peak value has been employed instead.

Since the monitor is being installed as a substitute for the ear, it is pertinent to inquire whether the ear responds to the peak, r.m.s. or average value of a sound wave. I do not think the ear integrates a sound, and hence the monitor may be insensitive to distortion which the ear might otherwise detect.

Presumably a system employing octave-band filters could have been used for monitoring the programme. A sample could be taken over a predetermined time-interval, and after rectification compared with a preset d.c. level. An alarm connected to each octave output would give a useful indication of harmonically related faults, as well as faults due to amplitude overloading.

Finally, I have found it very confusing in noting that the term of maximum input volume is "zero-volume," i.e. 0 db is 100% modulation. It would have been reasonable to expect that 0 db would have been at some inherent noise level.

Mr. D. R. Parsons: I do not think the automatic monitor, cleverly conceived as it is, has much application to the relay industry. Indeed I feel its use in the B.B.C. should be more restricted than it is to-day, particularly in the North-East area. The one great point in favour of the apparatus is that it is consistently alert. Alertness in human operating depends upon:

(*a*) Shifts being reduced to practical limits of duration.

(*b*) Interest in the programme being sent out by the operator concerned.

In connection with (*b*) I cannot agree that the work is most monotonous, particularly when foreign-language programmes are being monitored, which call for judgment or initiative. Obviously one has to have a monitor who understands the language being broadcast, and I understand the B.B.C. do this at their receiving stations, so I cannot agree that this point should be neglected at the sending end. Besides monitoring the service, the relay operator is, after office hours, the sole contact with the listener and is responsible for sending out maintenance men to any subscriber who reports faulty service. It should be remembered that any background noise that any relay subscriber reports is usually looked upon as crosstalk, whereas the listener with a broadcast receiver is so used to adjacent-channel breakthrough that he would not complain directly to the B.B.C.

This brings me back to the point of the restriction of the use of the automatic monitor by the B.B.C. in the North-East. The whole system works on the presumption that one has a sending point A with manual operation, and if the signal is sent on to points B, C and D, no manual operator is required at B and C as long as reference from A is available at the intermediate points B and C. A man is also listening at the end of the chain at D. However, if one takes a programme off a spur between A and B or B and C or C and D no such listening reference is available. Technically the circuit design is excellent, but when one is feeding programmes to half a million people in the North-East as does the organization with which I am connected, I feel the expense of operators on a shift basis is justified. After all, no electrical circuit can ever have any degree of responsibility.

I notice that in Fig. 5 the lowest noise operation curve is only 40 db down on programme volume. Does this mean that the

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* Paper by H. B. Rantzen, F. A. Peachey and C. Gunn-Russell (see 1951, 98, Part III, p. 329).