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THE RELATIONSHIP BETWEEN CATHODE EMISSION, CATHODE RESISTANCE AND MUTUAL CONDUCTANCE IN RECEIVING VALVES

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SUMMARY

The paper is divided into three parts, concerned respectively with the measurement of cathode emission and resistance and with the relationship between these two parameters and the mutual conductance of a pentode receiving valve.

Part 1 describes a method of extrapolating the zero-field total cathode emission at normal operating temperatures from the low-temperature emission measurement. It is shown that the final result is independent of contact-potential variations or potential drops across cathode, interface or collector films. The cathode work-function can also be derived from the extrapolation.

The inadequacies of existing methods of measuring cathode resistance in normal valves are considered in Part 2, which examines the possibility of substituting an empirical relation between emission and resistance whereby the average cathode resistance for a batch of valves may be quickly computed from the average cathode emission.

In Part 3 are devised relationships between the state of the cathode and mutual conductance of the valve which are based on theory and experiment. These form models which may be compared with the life-test measurements of mutual conductance and low-temperature total emission. It is found that the model which accords best with the life-test results is that which employs the concept of the cathode state being a function, not of emission alone, but of emission and resistance together.

In reaching this conclusion it is apparent that the validity of the comparison between the models and the life-test results must stand or fall by whether the assumptions which must be made in connection with the cathode work-function can be justified. With one exception it does, in fact, prove possible to justify all the assumptions required: the exception indicates, however, that the relationships which form the acceptable model have a limited, not a general, application.

LIST OF SYMBOLS

I, I_{g1} = Collector current in triodes or pentodes with control grid used as collector, mA.
I_S = Total cathode emission, amp.
$(I_s)_N$ = Total cathode emission at 1 020° K, amp.
$(I_s)_{LT}$ = Total cathode emission at P_h = 400 mW, amp.
I_a = Anode current, mA.
I_∞ = Collector current at onset of retarding field conditions for cathode of infinite total emission, mA.
V = Collector voltage, volts.
V_{g1} = Applied control-grid voltage, volts.
V_0 = Value of V_{g1} at the onset of total or saturated emission, volts.
V_I = Voltage drop across any cathode-core interface, volts.
V_M = Voltage drop across the cathode matrix, volts.
V_F = Voltage drop across any collector film, volts.
V_S = Voltage drop across the vacuum at the onset of total emission, volts.
V_m = Negative minimum voltage, volts.
V_G = Equivalent diode voltage, volts.
V_a = Anode voltage, volts.
V_{g2} = Screen voltage, volts.
V_h = Heater voltage, volts.
V_c, V_{CP} = Contact potential between grid and cathode, eV.
P_h = Heater power, mW.
g_m = Mutual conductance of pentode, mA/volt.
F_1', F_2, μ_{12}' = Constants from Liebmann's paper.
α = Pentode ratio (cathode current)/(anode current).
R_k = Cathode resistance, ohms.
d, S = Cathode-collector distances, m and cm, respectively.
x_m = Distance of space-charge voltage minimum in front of cathode, m.
T = Cathode temperature, °K.
A = Cathode area, cm².
$A^{(n)}$ = Constant in emission equation (6), amp-deg^{-n}.
$\frac{e}{k} = \frac{\text{electron charge}}{\text{Boltzmann's constant}}$, 11 606° K per volt.
q = Constant in eqn. (13).
σ_M = Matrix conductance, ohm^{-1}.
ϕ_C = Total work function of the collector, eV.
ϕ, ϕ_K, ϕ_1, ϕ_2 = Total work function of the cathode, eV.
ϕ_e = External work function of the cathode, eV.
$\phi^{(n)}$ = Total work function of the cathode referred to eqn. (6), eV.

Part 1. THE MEASUREMENT OF CATHODE EMISSION

(1) INTRODUCTION

It is well known that the mutual conductance of a receiving valve changes with time: at a constant anode current it deteriorates at a rate depending on the quality of the valve. It is also known that the total or saturated emission obtainable from an oxide cathode deteriorates with time and that the cathode resistance increases with time. There is general qualitative appreciation that the deterioration in emission and the increase in resistance are probably the direct cause of the falling mutual conductance. The quantitative links are not so easily determined, and this is in large measure due to the difficulties inherent in the measurement of cathode emission and resistance in a normal valve. The measurements must, of course, leave the characteristics of such a valve entirely unchanged after they have been completed. It is also impossible to make use of any artifice involving special valve construction (such as cathode probes for example) since, by definition, the measurements must be undertaken on a completely normal valve.

The paper considers the techniques available for such measurements and examines reasonable quantitative relationships between cathode emission, cathode resistance and mutual conductance.

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(2) THE TWO ALTERNATIVE TECHNIQUES OF EMISSION MEASUREMENT

At normal cathode temperatures (~1 000° K) the measurement of zero-field total electron emission from the oxide cathodes of valves intended for space-charge-limited operation has always presented a problem. Direct measurement of normal-temperature total emission is possible only if a pulse technique is used with high collector voltages applied to the control grid. This necessitates extrapolation to zero-field conditions. An approach to the zero-field condition is important on theoretical grounds and also in practice, since the equivalent diode voltage under space-charge-limited operation is usually only of the order of 0·5 volt. Alternatively, d.c. measurements at acceptable power dissipations are practicable only at sub-normal cathode temperatures, although a closer approach is made to the zero-field requirement.

Additional difficulties arise under pulse conditions, since the measurement itself may impair the emission if the valve is not free from gas and if there are films on the collector. Both measurements are subject to doubts arising from lack of knowledge of potential distributions across the cathode and collector and from uncertainties in contact-potential variations.

Over the past few years those engaged on thermionic-valve investigations in the Post Office have found it necessary to make comparative emission measurements on large numbers of valves. It was therefore desirable that the apparatus used should be simple, permit a rapid testing rate and present no difficulty in co-ordinating agreement between different investigators. The d.c. measurement at low temperatures, requiring essentially only voltmeters, milliammeters and l.t. accumulators, is particularly suitable in these respects, and has therefore been adopted as a standard technique. Because of the difficulty of extrapolating from low to normal temperatures, measurement at the former temperature has been used by itself as a basis for comparative emission studies; some justification of this procedure is considered in Part 3.

The low-temperature technique has been described by Metson, Wagner, Holmes and Child,[3] and the basic details of the method still apply. Improvements have been made in the control of heater power and in the testing rate to such an extent that it is now practicable to measure the emission of 10 valves in about 5 min.

The difficulties of the double extrapolation to zero field and normal temperature are considered below, and a more elaborate technique is described whereby extrapolation may be effected. Greater reliability and additional data are, of course, obtained only at the expense of a slower testing rate, and it is as a supplement to, and a check of, the standard method in isolated cases that the new method will find its greatest use.

(3) MORE DETAILED EXAMINATION OF THE LOW-TEMPERATURE MEASUREMENT

The measurement described in the earlier paper[3] is undertaken at one heater power (400 mW for a 2-watt heater) corresponding to a cathode temperature of about 700° K, and the collector voltage applied to the control grid is kept constant at 5 volts. These conditions correspond to measurement at a single point, P, on a typical $\log I_{g1}/V_{g1}$ characteristic, as shown in Fig. 1. A family of curves exists for any one cathode, each being similar to that shown in Fig. 1 and identified by a particular cathode temperature.

It is useful to identify the component parts of the $\log I_{g1}/V_{g1}$ curve with the potential diagrams of the cathode-collector system. The curve in Fig. 1 comprises three parts, AB, BC and CD. AB corresponds to retarding field conditions with no

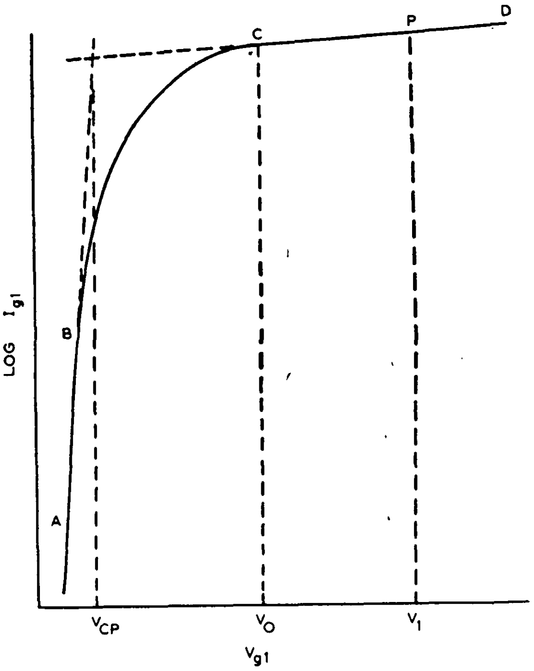

Fig. 1.—Typical $\log I_{g1}/V_{g1}$ characteristic of a modern receiving valve ($T \sim 700°$ K).

potential minimum existing between cathode and collector surfaces; under the conditions corresponding to B a potential minimum appears at the surface of the collector, giving a zero potential gradient or zero field at that surface. BC corresponds to space-charge-limited conditions with the potential minimum occurring in the space between collector and cathode; at C there occurs the onset of total or saturated emission as the potential minimum disappears into the surface of the cathode and zero-field conditions apply. The part CD corresponds to Schottky accelerating-field conditions, once again without a potential minimum between cathode and collector.

It is clear that the condition represented by the point C is the one which is of most interest for zero-field emission, and the relevant potential diagram is shown in Fig. 2. Here the Fermi

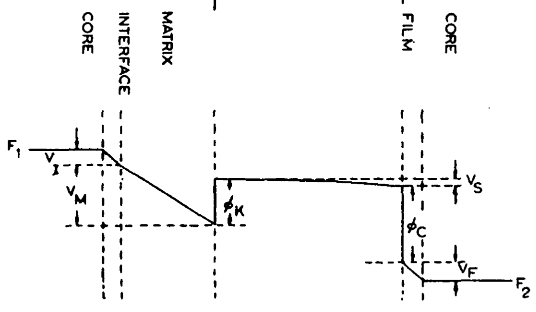

Fig. 2.—Voltage diagram of an oxide-cathode diode at onset of saturation (Point C, Fig. 1).

level, F_1, of the cathode core is used as a reference and positive voltages are measured downwards. The voltage difference between the Fermi levels F_1 and F_2 of the cathode and collector cores corresponds to the voltage applied externally to the cathode-collector system, i.e. to V_0 in Fig. 1, with the collector positive with respect to the cathode. It can be seen from Fig. 2 that

$$V_0 = V_I + V_M - \phi_K + V_S + \phi_C + V_F \quad . \quad . \quad (1)$$

Now the contact potential between the cathode and the collector is given by

$$V_{CP} = \phi_C - \phi_K$$

taken here as positive if $\phi_C > \phi_K$. Thus

$$V_0 = V_I + V_M + V_S + V_F + V_{CP} \quad . \quad . \quad . \quad (2)$$

the signs of all terms being positive if $\phi_C > \phi_K$.

Consequently, when measuring total emission from a cathode under conditions corresponding to the point P in Fig. 1, at a constant applied collector voltage, the emission is subject to a field effect dependent in some way upon the voltage difference $V_1 - V_0$, and therefore upon V_0. If several measurements of emission are taken under the condition P at different low temperatures, and are used to extrapolate to the emission at normal temperatures, then it is implied that either V_0 is invariant with temperature or the field effect is negligible. It will be shown in Section 5 that the field effect is certainly not negligible, and, through examination of the temperature dependence of the terms on the right-hand side of eqn. (2), it will be shown in the next Section that V_0 is not independent of temperature. Consequently, the extrapolation described is invalid.

(4) TEMPERATURE VARIATION OF THE FIELD EFFECT

The terms on the right-hand side of eqn. (2) have different degrees of temperature dependence. It is reasonable to assume, for instance, that V_{CP} is substantially constant with temperature over a range of about 150° K when p.d.'s which affect the issue are of the order of 0·1 volt.

For the voltage drop across the cathode matrix under saturation conditions the relation

$$V_M = I_S/\sigma_M \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

holds, so that $V_M \propto \varepsilon^{-e\phi_0/kT}$

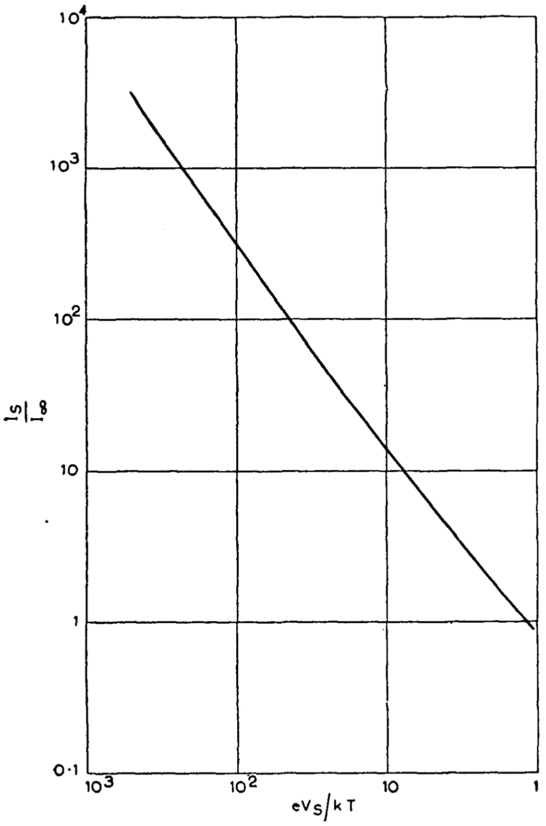

Fig. 3.—General curve relating emission, I_s, and cathode-collector voltage, V_S, at onset of saturation.

Under these circumstances there is a definite dependence of V_M on temperature.

A relation similar to eqn. (3) holds for V_I and V_F if an interface layer or a collector film is present. In these cases, however, I_S still refers to the cathode emission current, whereas the conductance term refers to either the interface or the film. It is unlikely that the total work function of the cathode will equal the internal work function of either the interface or the film—the only condition which would give temperature independence. It is therefore probable that V_I, V_F and V_M are temperature dependent, although it would not be easy to determine experimentally the quantitative nature of the dependence.

It remains to consider the voltage drop between the cathode and the collector surfaces which produces a potential minimum at the former surface, and here a theoretical determination of the temperature dependence can be attempted. The magnitude of V_S can be derived from Langmuir's equation relating space-charge-limited current with the cathode-collector voltage in a diode system. A simplified method of treating this problem has been developed by Ferris,[9] and using his approach it can be shown that V_S increases with temperature. Two curves are included to illustrate this change: Fig. 3 is a general curve relating $\log I_S/I_\infty$ and eV_S/kT, where I_∞ is a constant used by Ferris—a function of valve geometry and temperature which is defined as the current corresponding with the point B in Fig. 1 for a cathode of infinite emission. It is possible to derive further curves from this general curve which will relate V_S and T for any particular level of cathode emission and any diode system. Fig. 4 shows an example for the following special conditions:

(i) A total cathode emission given by the equation

$$I_S = 100T^{5/4}\varepsilon^{-e\phi/kT} \text{ amperes} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

with $\phi = 1 \cdot 1$ eV.

(ii) A diode system defined by

$$I_\infty = 0 \cdot 245 \times 10^{-3}\left(\frac{T}{1\,000}\right)^{3/2} \frac{A}{S^2} \text{ milliamperes} \quad . \quad . \quad (5)$$

where A = Cathode area = 0·45 cm².
S = Cathode-collector separation = 0·015 cm.

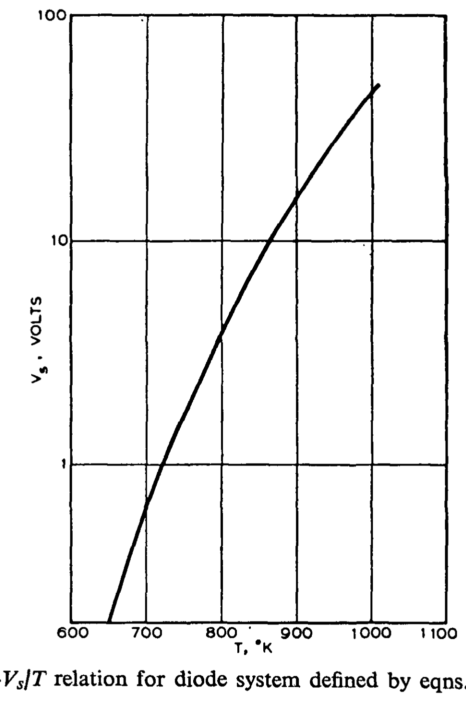

Fig. 4.—V_s/T relation for diode system defined by eqns. (4) and (5).

On the basis of this discussion it is clear that V_0 is temperature dependent. It is also clear that it is difficult to determine the theoretical value of V_0 at different temperatures, because it is so dependent on work functions which are not easy to determine experimentally on normal valves. It is also difficult to determine V_0 from the deviation of DCB in Fig. 1 from a straight line to a curve, owing to the restricted length of CD. (The voltage corresponding to the point D should not exceed 5 volts, owing to the danger of film breakdown.)

(5) AN ALTERNATIVE APPROACH TO THE FIELD CORRECTION

An alternative approach to the problem of correcting for the field effect in the low-temperature emission measurement may be seen by considering in more detail the curve obtained by recording emission measurements as a function of temperature at constant collector voltage. This curve was rejected in Section 3 as a basis for extrapolation owing to lack of means of assessing the field effect. The curve is, of course, a plot of $\log I$, the recorded emission, against $1/T$ at constant voltage, and a typical example is shown in Fig. 5 (curve SRQ) for a collector voltage of 3·5 volts.

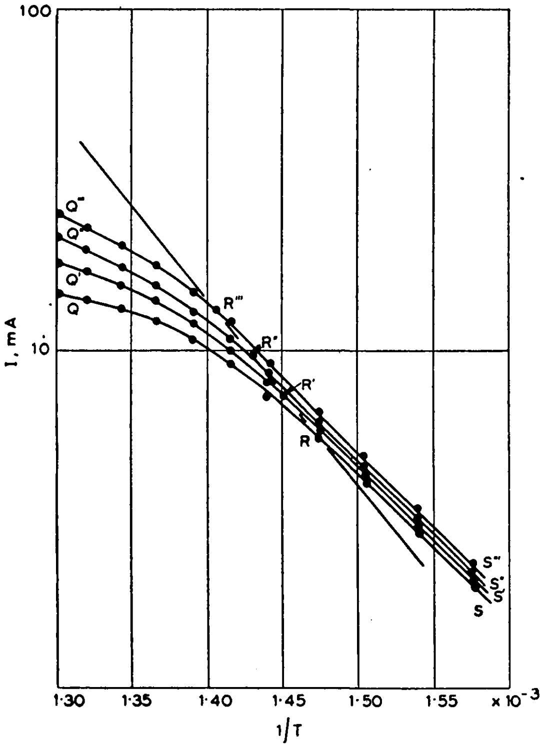

Fig. 5.—Typical $\log I/(1/T)$ characteristic with collector voltage, V_1, as a parameter.

The rejected extrapolation is the straightforward extension of SR to give an emission value at normal cathode temperature.

Referring once again to Fig. 1, it will be appreciated that P for a collector voltage of 3·5 volts may be in the region CD, may coincide with C or may be in the region BC, as the temperature increases. This is, in the first place, due to the fact that V_{CP} is substantially constant, as was pointed out in Section 3. The location of P in connection with the three possibilities, CD, C or BC, is therefore dependent on the magnitude of $V_0 - V_{CP}$. Now it can be shown [eqn. (2)] that $V_0 - V_{CP} = V_M + V_S$, provided that there is no interface or collector-film resistance. It can also be shown that the increase of V_S with temperature is the controlling factor when considering the changes of $V_M + V_S$, and therefore of $V_0 - V_{CP}$ with temperature over the range 650–750° K. At very low temperatures, P will be in the region CD and the measurement will be made under accelerating field conditions. As the temperature rises, the increase of V_S will cause $V_0 - V_{CP}$ to increase, and C will move towards P. When P coincides with C the space-charge minimum will just appear at the cathode surface and will cause a zero off-cathode potential gradient. As the temperature increases further, C will pass further to the right and P will fall in the region BC, where space-charge-limitation applies.

In Fig. 5 the portion of the curve SR is identified with the location of P in CD, i.e. with accelerating field conditions, and the portion of the curve RQ is identified with the location of P in BC, i.e. with space-charge-limited conditions; the point R, where the straight line SR becomes the curve RQ, is identified with coincidence of P and C, i.e. with zero off-cathode potential gradient. Thus R can be regarded as the only point on SRQ measured under effectively zero field conditions and the emission at that point will be independent of any considerations of contact-potential variations or potential drops across the cathode, the interface or the collector film.

The points R′, R″ and R‴ are also measures of zero field emission at different temperatures, being derived from curves having collector voltages V_1', V_1'', V_1''', equal to 4·0, 4·5 and 5·0 volts respectively. Now all the emission equations, of which

$$I_s = A^{(n)}T^n \exp(-e\phi^{(n)}/kT) \quad . \quad . \quad . \quad . \quad (6)$$

is the general form, imply a zero field. [The use of (n) as distinct from n implies an identifying superscript as distinct from a power index.] It is therefore argued that R, R′, R″ and R‴ are the only points in the $\log I_s/(1/T)$ field of Fig. 5 which may be used to extrapolate the emission to normal temperatures. If this is done, the form of emission equation implied is that due to de Boer, where $n = 0$ in eqn. (6).

As is well known, it is not possible to discriminate experimentally between the several emission equations using different values of n, such as $n = 0$ (de Boer), $n = \frac{1}{2}$ (Richardson) and $n = 5/4$ or 2 (semi-conductor theory). Here the use of $n = 0$ is taken for experimental convenience rather than in support of the de Boer equation against the rest. The value of work function so derived is $\phi^{(0)}$, but, if necessary, the points R, R′, R″ and R‴ can easily be replotted to conform with any other chosen form of index, e.g. 2 or 5/4. If this is done the values of work function are not very different, being reduced from the $\phi^{(0)}$ value by 0·05 to 0·1 eV.

Before proceeding to a more detailed consideration of the experimental method and results in the next Section, it is worth while commenting on Fig. 5, which forms the basis of this Section. First, the compensation for the field effect is seen to be of considerable importance. Extrapolation of SR to 1 000° K yields a normal-temperature emission of 700 mA, while extrapolation of RR‴ yields 2·2 amp. The value of $\phi^{(0)}$ based on RR‴ is 1·08 eV, and a work function of 0·86 eV may be calculated on the basis of SR, but while 1·08 eV is within the range of work functions generally accepted for the (BaSr)O cathode, 0·86 eV is not.

The linearity of the SR plot, which enables the onset of space-charge limitation to be defined at R, where curvature starts, is due to the fact that the relation between V_S and T is roughly linear over a limited temperature range. It is interesting to note that, moving to the right from R along RS, V_S decreases with decreasing temperature. There comes a time, as V_S decreases sufficiently in magnitude, when the relatively slow change of V_M with temperature supervenes. At this point the $\log I_s/(1/T)$ plot increases noticeably in slope, i.e. takes an abrupt kink downwards. Fortunately this occurs at a temperature between 50 and 100° K lower than the zero-field point (it occurs where $10^3/T = 1\cdot6$ in Fig. 5). This permits the linearity of SR to be estimated over a reasonable range.

(6) EXPERIMENTAL DETAILS AND RESULTS

A simple circuit such as that shown in Fig. 6 has proved to be very suitable for measuring the curves shown in Fig. 5. The low

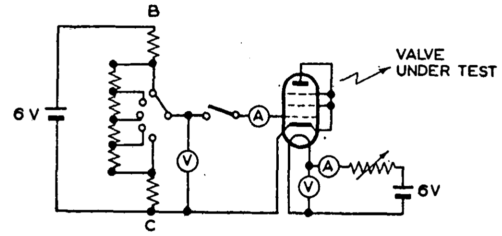

Fig. 6.—Circuit used for emission measurements.

resistance ($\sim$6 ohms) of the voltage divider BC provides substantially constant voltage sources of 5·0, 4·5, 4·0, 3·5 and 3·0 volts, although it will be realized that the precise value of the voltage is immaterial, provided that it remains constant.

If a single valve type is being tested, a common heater-power/cathode-temperature relationship can be used without serious error. Thus the heater power is set at some particular value and the collector currents are recorded for the four or five collector voltages. Four or five points are therefore obtained on the $\log I/(1/T)$ curves at one value of $1/T$. The readings are repeated at different heater powers. The measurements necessary to complete a set of curves can be taken in about 15 min, allowing about 1 min for the cathode temperatures to become stabilized before all readings except the first, where 3 min should be allowed from cold conditions. All heater-power and collector-voltage changes are made with the control-grid key open, and the collector current readings are taken by momentary depression of the key.

From experience the lowest values of I which need to be recorded, corresponding to S, S′, etc., are of the order of 1 mA at a cathode temperature of about 640° K. The points Q, Q′, etc., will have been reached in almost all cases before I reaches 20 mA and before T reaches 760° K. In many cases it will be found unnecessary to record currents higher than 10 mA. Because of film breakdown, the highest collector voltage used is 5 volts. In general, about 10 sets of readings at 10–15° K intervals will be found adequate. The whole family of curves is shifted to the left for valves with poor emission levels, and to the right for exceptionally good valves.

The distance over which RR‴ must be extrapolated is substantial if the valve is good, and is much reduced as the valve deteriorates. Support for the reliability of the extrapolation is derived from the results quoted in the next paragraphs. The values of ϕ and total emission at normal temperatures are in agreement with generally accepted results, and in addition, some correlation is found between results obtained using this extrapolation and results depending on extrapolation from pulse measurements.

Values of $\phi^{(0)}$ [eqn. (6)] for 27 valves are plotted in the form of a histogram in Fig. 7, together with extrapolated values of I_s at 1 020° K (roughly equivalent to $V_h = 6\cdot0$ volts). It will be seen that a mean value of $\phi^{(0)}$ of about 1·4 eV is obtained, which would give a value of $\phi^{(5/4)}$ of about 1·3 eV. The mean normal-temperature emission of about 1·5 amp corresponds to 3 amp/cm². The valves are of the deep-sea repeater type, and

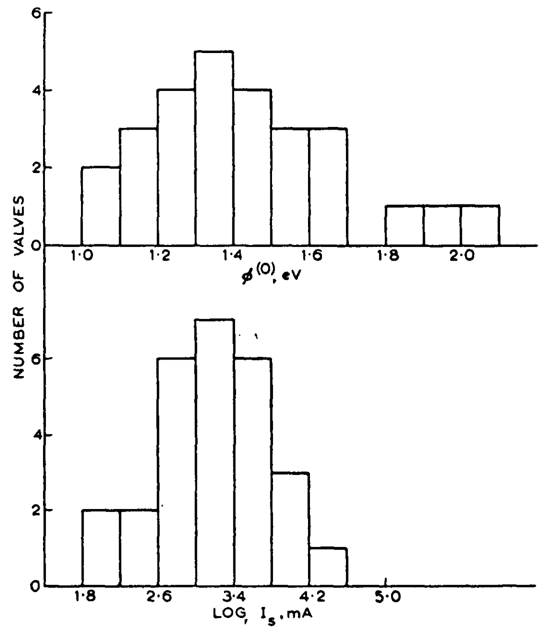

Fig. 7.—Values of $\phi^{(0)}$ and I_s at 1 020° K for 27 valves.

almost all of them have platinum cores. Within the relatively small sample no clear correlation could be detected between $\phi^{(0)}$ and I_s, i.e. that high values of I_s, for example, are not uniquely associated with low values of $\phi^{(0)}$.

One other item of interest should be noted. The measurements on the 27 valves were made whilst they were on life tests and after varied periods of time. If the average work functions are considered on a time basis, the following information can be derived:

Valves measured	*Average value of $\phi^{(0)}$* eV
Between 0 and 500 hours	1·3
Between 500 and 1 500 hours	1·4
Over 1 500 hours	1·6

There is thus some evidence of increasing work function with life.

Despite the lack of a really successful pulse technique, an attempt was made to compare the emission of some valves measured under both pulse and low-temperature methods. For the pulse measurement, extrapolation to zero field was made using the Schottky line. Agreement to within about 20% was obtained in some cases; in others the pulse-derived emission was only 50% of the low-temperature derivation, although here clear indication of deterioration under the influence of the high-voltage pulse (100 volts) was obtained. It is, however, felt that a more rigorous comparison should be undertaken using single pulses in place of the pulse recurrence frequency of about 1 000 pulses/sec that is sometimes quoted.

Part 2. CATHODE RESISTANCE IN RECEIVING VALVES

(7) INTRODUCTION

The oxide cathode is of finite thickness and consequently has an associated conductivity and resistance. In the cathodes of most modern receiving valves the resistance has two components, namely that of the oxide coating itself and that of an interface layer between the coating and the metallic cathode core. It is not proposed to consider the interface layer in the paper, because the associated experimental work is based on valves whose cathodes do not develop interface resistances, namely valves with platinum cores. There is also a reasonable possibility of eliminating the interface entirely in future commercial valve production through the adoption of new cathode-core alloys. The technique for measuring interface resistance is, in any case, well known and is described in detail elsewhere.[1] The technique for measuring the resistance of the oxide coating itself, on the other hand, is very difficult, and a review of the problems involved is given in the next Section.

The resistance associated with the oxide cathode is not, so far as the paper is concerned, equated to any physical model. It has been suggested by Loosjes and Vink[2] that the mechanism of conduction through the coating consists of a combination of pore conduction and solid conduction, with the former predominating at normal cathode temperatures ($\sim$1 000° K). Most investigators favour this model, but the model requiring solid conduction alone has not been entirely excluded. Although a detailed physical model is not required here, it will be seen that certain properties of the oxide-cathode resistance are stressed by the results obtained in later Sections.

(8) THE MEASUREMENT OF CATHODE RESISTANCE

The measurement of cathode resistance on normal receiving valves is subject to the same limitations that apply to the measurement of cathode emission. The measurement must leave the characteristics of the valve unchanged after completion and must be undertaken without the use of any special valve construction. This second limitation immediately excludes the only really reliable methods of resistance measurement, namely the use of embedded probes or measurements on cathode blocks between large electrodes.

Despite these limitations, attempts have been made to measure cathode resistance in normal valves. Two methods have been suggested which are based on the shape of the current/voltage characteristic, using the control grid as collector, one being based on the displacement[3] of the characteristic and the other on the curvature[4] of the characteristic in the retarding field region. Both methods suffer from the disadvantage that the derived resistance includes the resistance of any film present on the collector, and both give results which vary with cathode current, i.e. they vary with that portion of the current/voltage characteristic used to make the calculation. The reason for this is not completely understood, and the quantitative basis for the variation is lacking. Thus it is not considered profitable to use this type of measurement at this stage, although information gained in such measurements is used in framing a hypothesis to test against experimental evidence.

In the discussion on Reference 3 Eaglesfield suggested that measuring the shift in the grid-voltage/grid-current characteristic when screen-grid current is caused to flow by an applied voltage was the simplest method which might be applied to a normal valve for the derivation of cathode resistance. The results yielded are of the right order, but are subject to variations depending on the grid current used to measure the shift of the characteristic and on the screen-grid voltage. This lack of precision is fundamental to the method and has prevented its use here. Finally, Nergaard[5] has suggested an equivalent circuit which may be employed in a bridge network in order to determine the values of R and C to be associated with the oxide cathode, against which the equivalent circuit is balanced. This type of method has been criticized by Tillman, Butterworth and Warren[6] in their work on the dependence of mutual conductance on frequency. They hold that, even when considering the interface impedance on its own, its representation as two elementary components only is inadequate for the explanation of certain experimental results. It is consequently felt that the combined representation of oxide cathode and interface by the networks suggested by Nergaard may require qualification.

At the moment, all available methods of measuring the resistance of the oxide cathodes of normal receiving valves require some form of qualification, and thus none of these methods will be used directly in the examination of the relationship between emission, resistance and mutual conductance. As an alternative approach it is proposed to calculate the resistance of the cathode from the emission in a manner which has some experimental justification. The validity of the calculation will then be examined against other critical experimental data.

(9) CALCULATION OF CATHODE RESISTANCE

In order to calculate the resistance of the cathode, use is made of the proportionality of emission and conductance reported by Metson *et al.*[3] and by Hannay *et al.*[10] A comparison was made between the resistances of oxide cathodes measured by Dalman's method and by the method used in Reference 3. The results were of the same order in both cases, and because of the mutual support it was decided to use the proportionality equation [eqn. (8)] from Reference 3 in this investigation. The equation is more conveniently expressed as

$$I_s R_k = 1 \cdot 6 \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Although this equation was established at low cathode temperatures (700–800° K), it is intended to extend its use up to normal cathode temperatures ($\sim$1 000° K).

A corresponding equation can be deduced from Hannay, MacNair and White's paper[10] with a figure of 0·5 in place of the 1·6 used in eqn. (7). Additional comment on the choice of 1·6 will be given in Section 13.

When considering the relationship between emission, resistance and mutual conductance in the Sections which follow, eqn. (7) will be used, with other factors, to derive relationships between the state of the cathode and the mutual conductance of the valve. When using eqn. (7) in any context the emission and resistance must, of course, be measured at the same temperatures. If the equation is applied at normal temperatures, it is the normal-temperature total emission which is involved. This may be derived from the method described in Part 1, but, if many valves are to be subject to examination, this procedure would consume excessive time. Alternatively, an approximate calculation of the normal-temperature emission can be made by using the equation

$$(I_s)_N = 1\,000(I_s)_{LT} \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

This relation can, of course, best be used when considering the average results for batches of valves, rather than in individual cases. It can be justified to some extent for batch treatment in that the multiplying factor of 1 000 used in eqn. (8) assumes a value of $\phi^{(0)}$ of 1·32, which is in reasonable agreement with the experimentally determined average value of $\phi^{(0)}$ taken from Fig. 7. It is appreciated that the use of eqn. (8) implies a constant cathode work-function, not only from valve to valve, but also with life, and that one conclusion reached in Part 1 was that there was some evidence of an increasing work function with life. It is nevertheless intended to use the equation and, by comparison with experiment, to observe when it breaks down, so obtaining additional information on the trend of change of work function. Further consideration of this trend will be deferred to Section 13.

Before closing this Section a final comment on the use of eqn. (7) is necessary. The general objections to the method of resistance measurement used in deriving this equation were stated in the second paragraph of Section 8. The first objection, the inclusion of any unwanted collector-film resistance, was eliminated in the data used to establish eqn. (7). This was made possible in unpublished work by Child, who confirmed the absence of such films in the particular valves involved, using a 2-frequency method. The second objection, the variation of computed cathode resistance with cathode current, must stand. Here the use of the equation can be justified only through comparison of the results obtained from its application with other experimental evidence. This comparison will be made in Section 12.

Part 3. THE RELATIONSHIP BETWEEN CATHODE EMISSION, CATHODE RESISTANCE AND MUTUAL CONDUCTANCE

(10) INTRODUCTION

Before considering the relationship between cathode emission, cathode resistance and the mutual conductance of the valve, it is necessary to refer briefly to the experimental derivation of the mutual conductance. All the measurements reported here were made with an a.c. bridge method at a frequency of 1 kc/s with a control-grid signal amplitude of about 50 mV, d.a.p. The repeatable accuracy of the bridge is considered to be about 0·1%; the absolute accuracy is good, but is, of course, dependent on the accuracy of the meters (among other components) used.

The following plan will be used to study the interdependence of these parameters: First, it is possible to calculate a relationship between the total emission of the cathode and the mutual conductance for a particular valve structure, and the manner of doing this is described in Section 11. Second, it is possible to take the calculation a stage further and allow for the effect of cathode resistance. We then have two relationships, the first between cathode state, judged on emission alone, and mutual conductance, and the second between cathode state, judged on emission and resistance, and mutual conductance. These form two models which may be set against experimental data to see which provides the closer fit. It will be shown that the large-scale life tests undertaken at the Post Office Research Station provide a block of experimental data which can well be used in assessing the validity of the two models.

Before leaving this introduction it is worth while to give some details of the life-test procedure. The valves concerned are pentodes of the Post Office types 6P10 and 6P12. The first is very similar to the CV 138, and the second is almost identical, except that the screen grid has been moved closer to the control grid in order to permit operation with $V_{g2} = 60$ volts, instead of the 250 volts required for the 6P10. Both types are run under constant-cathode-current conditions, achieved by high d.c. feedback (6 kilohms in the cathode lead offset by a stabilized positive potential of 50 volts applied to the control grid). Consequently any changes in contact p.d., or other factors affecting the valve working point, have a reduced effect on the currents drawn to anode and screen. The anode and screen voltages are also stabilized and the heaters are run from a stabilized a.c. source.

(11) THE RELATIONSHIPS BETWEEN CATHODE STATE AND MUTUAL CONDUCTANCE

The basic current/voltage relationship used in any treatment of valve operation is afforded by the Langmuir equation for a planar diode:

$$I = 2\cdot335 \times 10^{-6}\frac{(V - V_m)^{3/2}}{(d - x_m)^2}\left[1 + \frac{T^{1/2}}{40\cdot3(V - V_m)^{1/2}}\right] \quad . \quad (9)$$

In order to apply this equation to pentodes with substantially planar cathode surfaces, it is necessary to reduce the pentode structure to the equivalent diode, and here the treatment of the problem given by Liebmann[7] is followed. In particular, use is made of the cathode sectionalization described by Liebmann to allow for the variable-mu effect.

Since the total cathode emission, I_s, occurs in the derivation of V_m and x_m in Langmuir's equation, it is possible to construct a relationship between the emission and the mutual conductance of the pentode. A set of equivalent diode voltages, V_G, were calculated for a particular pentode structure, for particular values of screen voltage, V_{g2}, and contact potential, V_c, between the grid and the cathode, and for a series of control-grid voltages; Liebmann's equation

$$V_G = F_1'\left(V_{g1} + V_c + \frac{F_2V_{g2}}{\mu_{12}'}\right) \quad . \quad . \quad . \quad (10)$$

was used for this purpose, where the factors F_1', F_2 and μ_{12}' may be calculated from the valve geometry.[7] These values of V_G were then applied to Langmuir's equation as V, the collector voltage, to calculate the current/voltage relation for the equivalent diode at any chosen value of I_s. The computed values of equivalent diode current were then plotted against the value of V_{g1} used to compute V_G, so producing the cathode-current/grid-voltage characteristic of the pentode. This characteristic was transformed to the anode-current/grid-voltage curve through the application of a suitable factor, α. Further curves of this type were calculated for different values of I_s, and from this set of curves it is possible to derive another family with mutual conductance plotted against I_s, having constant I_a as parameter. This family of curves provides the first model for the relationship between cathode state, as measured by emission alone, and mutual conductance.

In this connection it should be remembered that no assumption is made in Langmuir's equation as to the cause of different values of I_s. The calculation is developed from Child's law, where the initial velocities of the electrons are neglected, by making use of Maxwell's velocity distribution of the emerging electrons. Here, however, it is necessary to consider one aspect of the nature of the change of I_s. If I_s is assumed to change owing to a change in the work function of the cathode, the appropriate correction must be made to V_c and therefore to V_G. This correction has, in fact, been made in the calculations used here. It can, however, be shown that, so far as the relation between mutual conductance (at constant anode current) and total emission is concerned, the correction is immaterial. The same result is obtained, within the accuracy of the computation used, as if the contact potential had been assumed to be constant. The major effect of the correction is in its control of the position of the I_a/V_{g1} characteristic along the grid base. If the correction is applied, the position of the characteristic remains substantially invariant with changing I_s, except for very low values of I_s, as first explained by Gysae and Wagener.[8] If the correction is not made, i.e. if I_s is assumed to change from some cause other than change of work function, the characteristics are spread over a much wider portion of the grid base. However, this difference is outside the scope of the investigation.

At a later stage in the paper it will be found necessary to use the concept of work function in order to translate low-temperature to normal-temperature total emission through use of eqn. (8) or some similar relation. This need arises in the attempt to check the validity of the model relation, developed above, against life-test records. The fact that the model is substantially independent of the concept of work function will exclude the complication of amending the model to suit the necessary work function adopted for the translation. The relative unimportance of work function and contact potential is doubly fortunate here, for it must be appreciated that the work function of the control grid is usually unknown.

Typical examples of calculated anode-current/grid-voltage characteristics and the complementary mutual-conductance/total-emission curves are shown in Figs. 8 and 9(*a*), the valve used

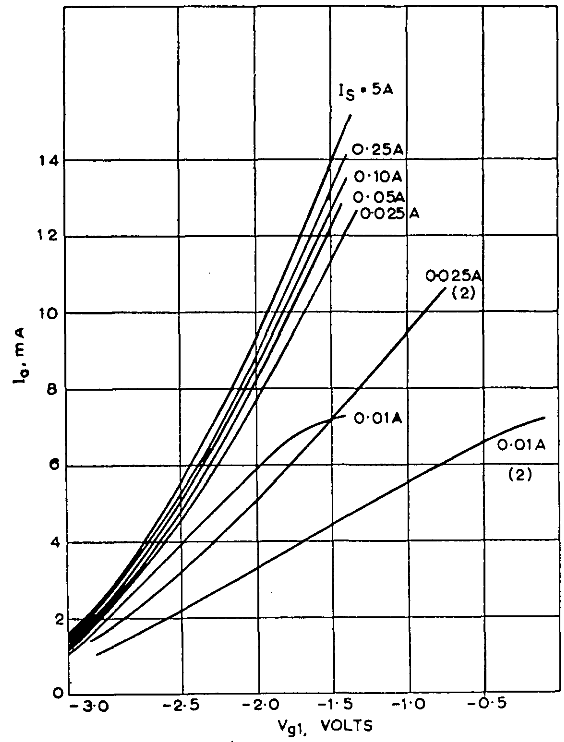

Fig. 8.—I_a/V_{g1} characteristics, with I_s as parameter, for the 6P10 valve, calculated in accordance with the first model.

The curves marked (2) show two of the characteristics modified by the inclusion of a cathode resistance inversely proportional to the emission I_s.

being the 6P10. The solution of the Langmuir equation was effected using the method developed by Ferris,[9] and a cathode temperature of 1 020° K was used for the calculation. The cathode-control-grid spacing is assumed to be 0·15 mm and the cathode area 0·45 cm^2, which gives $I_\infty = 0 \cdot 505$ mA at 1 020° K [eqn. (5)]. Values of I_s used were derived from values of I_s/I_∞ of 10 000, 2 000, 500, 200, 100, 50 and 20. Curves of I_a/V_{g1} were thus calculated for a range of total emission extending from 5 to 0·01 amp. A value of 0·8 volt was assumed for V_c at $I_s/I_\infty = 10\,000$, and a value of 1·1 eV for ϕ_K, the work function of the cathode, under the same circumstances. The following equation

$$\log_\varepsilon \frac{(I_s)_1}{(I_s)_2} = \frac{e}{kT}(\phi_2 - \phi_1) \quad . \quad . \quad . \quad . \quad (11)$$

was used to calculate changes in work function necessary to compute changes in V_c with total emission. A constant value of 1·9 eV for ϕ_c, the work function of the control grid, was assumed to hold throughout the calculations; this figure is, of course, derived from the initial values of V_c and ϕ_K. The I_a/V_{g1} curves were calculated for a screen-grid voltage of 250 volts.

As was stated before, Fig. 8 forms the first model of a relationship between cathode state and mutual conductance against which experimental results may be compared. Before such a comparison is made, however, it is proposed to derive a second model. The first is based on deterioration of the cathode due

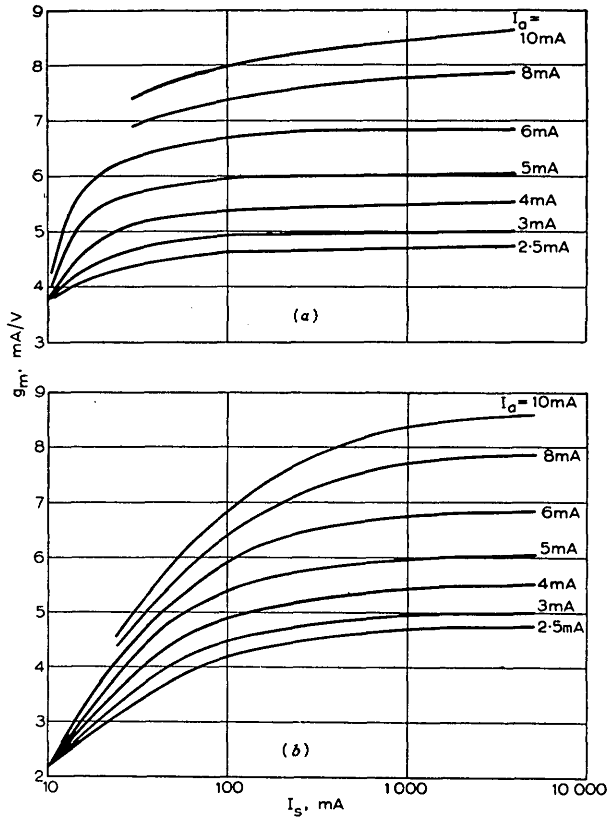

Fig. 9.—g_m/I_s characteristics, with I_a as parameter, for the 6P10 valve, forming the models linking the cathode state with the mutual conductance of the valve.

(*a*) First model.
(*b*) Second model.

to failing emission alone: the second will assume a decay in emission accompanied by an increase in cathode resistance. In order to form a reasonable estimate of the resistance to be associated with each level of emission in the first model, use is made of the experimental fact of inverse proportionality of emission and resistance derived from Reference 3 and from information provided by Hannay, MacNair and White,[10] although their interpretation of the underlying cause of inverse proportionality is not necessarily subscribed to. The cathode resistance for the second model is therefore calculated on the basis of the values of I_s used in the first model, in conjunction with eqn. (7). In order to formulate the second model it is possible to modify each I_a/V_{g1} characteristic in Fig. 8 by the addition of the appropriate cathode resistance, and then to produce from these a new set of g_m/I_s curves. Two such modified I_a/V_{g1} curves are included in Fig. 8. An alternative approach would be to modify Fig. 9(*a*) directly according to the equation

$$g_m = \frac{g'_m}{1 + R_K g'_m \alpha} \quad . \quad . \quad . \quad . \quad . \quad (12)$$

where g_m = New value of mutual conductance.
g'_m = Value of mutual conductance in Fig. 9(*a*).
R_K = Cathode resistance associated with the (g'_m, I_s) co-ordinates of Fig. 9(*a*), calculated according to eqn. (7).
α = Ratio cathode-current/anode-current (~1·25).

Hence each co-ordinate (g'_m, I_s) of Fig. 9(*a*) would be translated to (g_m, I_s) in a new family of curves shown in Fig. 9(*b*), which then forms a second model of a relationship between cathode state and mutual conductance. This model, however, takes account of reduction in emission together with a consequent increase in cathode resistance and is not restricted to the concept of falling emission alone as was the first model.

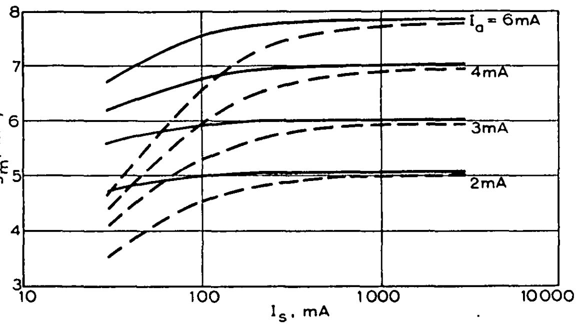

Fig. 10.—g_m/I_s characteristics, with I_a as parameter, for the 6P12 valve, forming the models linking cathode state with valve mutual conductance.

——— First model.
— — — Second model.

All the calculations necessary to provide these two models were then repeated for the 6P12. The two families of curves corresponding to Figs. 9(*a*) and 9(*b*) for the 6P10 are combined in Fig. 10 for the 6P12 for a screen-grid voltage of 60 volts.

(12) COMPARISON OF EXPERIMENTAL RESULTS WITH THE MODELS

Before any attempt at comparison is made between the models and experimental results taken from life-test records, one further difficulty must be resolved. This arises from the fact that the g_m/I_a relationship obtained from Langmuir's equation and valve design data, such as those suggested by Liebmann, is invariably more optimistic than the relationship obtained from measurement. This problem has been treated in unpublished work by Reynolds, and it is suggested that the discrepancy is due to difficulties in estimating the effective grid-cathode distance. Corrections due to variations in grid pitch, to cathode misalignment and to lack of control of the grid-wire diameter must also be considered in appreciating the difference between theory and practice.

For the purpose of this investigation it is proposed to overcome this difficulty by disregarding the parametric values of I_a in Figs. 9 and 10 in the following manner. The measured values of g_m, at constant I_a, and of the low-temperature total emission are extracted from the life-test records, and eqn. (3) is used to convert the low-temperature to the normal-temperature total emission. A plot of g_m against I_s at the several life test stages can then be made using the same axes as Fig. 9 or 10. The shape of the resulting curve may be compared with the family of curves comprising the first model or that comprising the second. In particular, the resulting curve may be compared with one curve from the family of each model. The curve chosen in each case is that which passes through the highest I_s co-ordinate taken from the life-test records, neglecting the fact that the constant I_a value of the experimental curve will not necessarily coincide with the parametric value of I_a in the curves chosen from the models. It will be realized here that the curves chosen for comparison with the life-test plot may not be any of those actually drawn in Fig. 9 or 10. The curves shown are merely examples of a complete family whose individual separations may be made as small as required.

This decision to disregard the parametric value of I_a in the models can be justified by comparing the curve for 8 mA in Fig. 9(*b*) with the second model curve for 6 mA in Fig. 10. Here we have two different geometrical structures giving similar values of g_m for different values of I_a. Nevertheless, the two curves almost coincide, and therefore it can be said that the decay of g_m with I_s, from initial values of 7·8 mA/volt and 1 amp, is independent of whether the parametric I_a value is 8 or 6 mA. That this can be said of two differently designed structures would make it even more applicable when considering minor modifications to the same structure.

The comparison between models and life-test records is first made in Fig. 11(*a*). Here the average values of g_m and I_s at

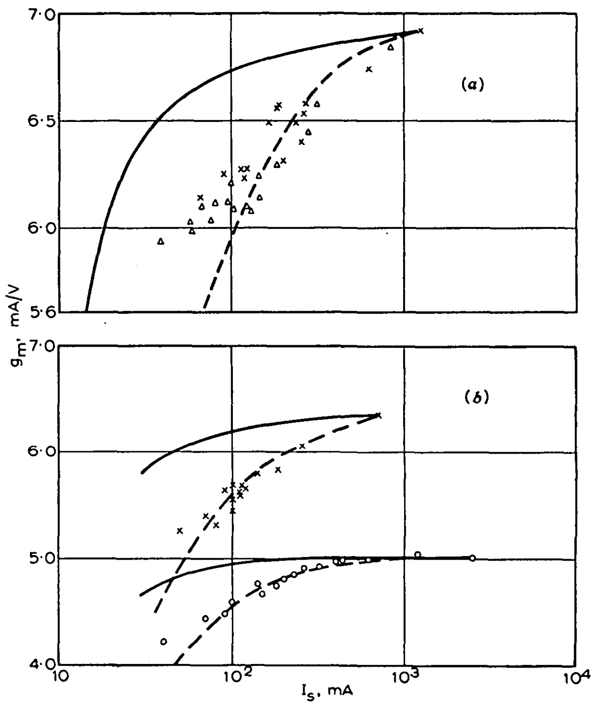

Fig. 11.—Comparison of two sets of average life-test measurements of g_m and I_s with selected curves from the first and second models.

——— First model.
— — — Second model.
(*a*) 6P10 valves.
(*b*) 6P12 valves.

several different stages of life test are obtained from the records of two batches of 10 valves of type 6P10. After eqn. (8) has been used to obtain an estimate of I_s at normal temperatures, the separate (g_m, I_s) co-ordinates for the two batches are plotted as crosses and triangles and compared with two model curves chosen in the manner described. In view of the fact that the highest (g_m, I_s) co-ordinates for each batch are almost coincident, a single curve from each model is shown for comparison. The life-test conditions in both cases were $V_a = V_{g2} = 250$ volts, $V_h = 6{\cdot}3$ volts and $I_a = 8$ mA.

A second comparison is made in Fig. 11(*b*) for two batches of valves of type 6P12, one of 50 valves, plotted as crosses, and one of 10 valves, plotted as circles. In this case a separate pair of model curves is required for each batch. The life-test conditions were $V_a = 90$ volts, $V_{g2} = 60$ volts, $V_h = 5{\cdot}5$ volts and $I_a = 6$ mA for the larger batch, and $V_a = V_{g2} = 40$ volts, $V_h = 5{\cdot}5$ volts and $I_a = 3$ mA for the smaller batch. At this stage two points should receive comment: first, a heater voltage of 6·3 volts for the 6P10 would give a cathode-surface temperature of about 1 020° K, which is the value chosen for the models (a heater voltage of 5·5 volts for the 6P12 would give a cathode-surface temperature of about 1 010° K, or 10° lower); second, the screen-grid voltage used in the life test of the smaller batch of 6P12 valves was 40 volts whereas that used for the models was 60 volts. Neither the difference in temperature nor the difference in voltage is thought to be significant: the temperature difference is considered to be negligibly small, and the voltage difference can be shown to be unimportant through examination of the g_m/I_a characteristics of valves with V_{g2} as parameter. These curves show that, although the value of g_m for any particular value of I_a differs with V_{g2}, the rate of change of g_m with I_a at particular values of I_a is substantially independent of V_{g2} in the acceptable operating region of the valve. This means that a change in V_{g2} merely produces a slightly different basic I_a/V_{g1} shape, equivalent to a minor geometrical modification. Thus, by disregarding the parametric values of I_a in the models, it is possible to disregard, not only geometrical uncertainties in the valve structure, but also differences in screen-grid voltage.

Although the experimental points in Fig. 11 are derived from life-test records, no reference to time is made in either Figure. In order to present the results in another way, the plots in Fig. 11(*b*) are represented as life-test curves in Fig. 12, where the full curves are the actual measurements of g_m taken during life test; the broken curves are the values of g_m computed from the life-test low-temperature emission results using eqn. (8) in conjunction with Langmuir's equation and Liebmann's design data, i.e. using the first model; and the dot-dash curves give g_m computed in the same way, through use of the second model. The computation is simply done by choosing the model curve which passes through the first (g_m, I_s) co-ordinate of the life-test record and subsequently reading off the g_m values for the sequence of emission levels of the life test.

In order to make the comparisons described in the preceding paragraphs, the actual measurements of low-temperature total emission are modified by eqn. (8) to translate them to normal temperatures before any comparison with a model is possible. For the small sample of 80 valves so far considered it would appear that use of this equation is not unreasonable when the low-temperature emission exceeds 150 μA, since the results obtained are fairly closely in line with the second model. In the following extension to much larger numbers of valves, however, modifications to eqn. (8) will be considered.

It is now proposed to consider life-test results on a much larger scale. The records of about 1 000 valves are examined over life-test periods ranging from 2 000 to 23 000 hours. These valves (and the preceding 80) were constructed to test the pre-processing of valve components and the use of non-standard piece-parts. They are all particularly useful for the present investigation, since the falls in g_m and I_s are, in general, considerably greater than those in standard valves of the same type. They therefore give greater opportunity for comparison between model and life-test records over substantially wider emission ranges.

The following method is used in the larger-scale investigation. First, the results presented in Figs. 11 and 12 are deemed sufficient to exclude the first model in favour of the second. This exclusion is supported in the review described below, where it can be shown that work functions less than 1 eV would be necessary to fit the life-test results to the first model. Such work functions are outside the range of those accepted in the literature or demonstrated in Part 1. (This point will be expanded in the next Section.) Consequently, in what follows, it will be assumed that only the second model, incorporating the idea of cathode resistance, need be considered. The life-test results are then taken in batches of 10–100 valves. The average values of g_m and low-temperature total emission at the start of life are used in conjunction with an equation of the form

$$(I_s)_N = q(I_s)_{LT} \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

similar to eqn. (8) to locate a particular model curve in Figs. 9 or 10. The choice of a specific value for q is deferred for a moment, but, assuming a choice is made, the average value of the end-of-life emission is also used in eqn. (13), with the same value of q, to determine an estimate of the end-of-life normal-temperature emission. This emission is used to determine the final g_m on the particular curve chosen, i.e. according to the second model, and this g_m is compared with the final g_m taken from the life-test records according to the equation

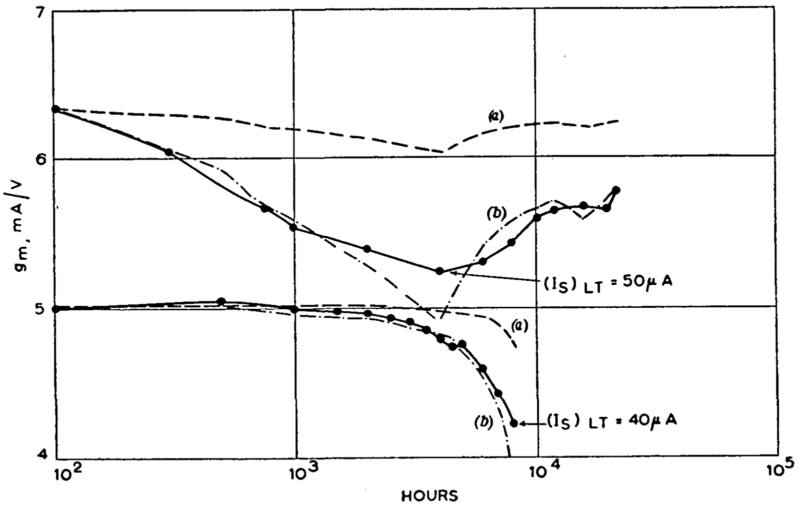

Fig. 12.—Comparison of experimental and calculated life characteristics of g_m for two sets of 6P12 valves.

The curves marked (*a*) indicate a calculation based on the application of the first model to life-test measurements of emission; the curves marked (*b*) indicate a similar calculation using the second model.

———— Experimental values.

— — — —, —·—·— } Calculated values.

Percentage agreement between life test and model =

$$100\left[1-\frac{|\text{Final } g_m \text{ from life test} - \text{Final } g_m \text{ from model}|}{\text{Fall in } g_m \text{ from life test}}\right] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

No account is taken of whether the second term inside the bracket has a positive or negative sign.

Before any results are presented, it is proposed to refer back to the choice of q in eqn. (13). When this larger-scale investigation based on the life-test records began it was found that, although a figure of 1 000 [cf. eqn. (8)] could be used for q very satisfactorily for a large number of 6P10 valves, a different value was more successful for other 6P10 valves and for 6P12 valves. It was therefore decided to divide the batches into 10 groups, according to valve types, life-test conditions, quality and final value of low-temperature emission. For each of the groups a value of q was chosen to the nearest 100 to bring the agreement expressed in eqn. (14) to at least about 90%. When making this choice it will be appreciated that the process of locating the model curve gives little information on the necessary value of q which must be adopted. This is particularly true when the initial low-temperature emission is greater than 1 mA. For example, the curve located by a g_m of 6·5 mA/volt and a low-temperature emission of 1 mA associated with a q of 500 is not very far removed from the curve located by the same g_m and emission associated with a q of 1 500. The reason for this is, of course, the fact that the model curves are all nearly parallel to the emission axis for emissions greater than 1 amp. As the emission diminishes and the model curves tend to become parallel with the g_m axis, so the choice of a value for q becomes more decisive in locating the required model curve.

Clearly q must finally be chosen to bring the recorded g_m at the end of life so close to a particular model curve that the 90% agreement is achieved. The particular model curve is located in the first place by the initial values of g_m and low-temperature emission in conjunction with eqn. (13) and any arbitrary value of q in the right range. A figure of 1 000 is quite reasonable here. In Table 1, after a final choice of q has been made, a minor correction is made to the initial choice of model curve by substituting the final value q for the arbitrary choice in the context of the initial g_m and emission values.

It will be observed from the previous two paragraphs that agreement to within 90% has been forced between life-test records and the second model. It is therefore not possible to justify the second model on the basis of agreement with experiment results, except in so far as it can be admitted that agreement is possible if the appropriate adjustments are made to q. The validity of the second model must stand or fall by whether the q modifications can be justified experimentally or on accepted previous experience of the underlying principles of the cathode. This aspect is treated in the next Section.

It should be emphasized that no special attempt was made to adjust q more precisely than to the nearest 100, although a closer percentage agreement could have been obtained in this way. The value of $\phi^{(0)}$ was calculated according to the equation

$$\log_\varepsilon q = \frac{e\phi^{(0)}}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right) \quad . \quad . \quad . \quad . \quad (15)$$

derived from eqn. (6) and reducing to

$$\log_\varepsilon q = 11\cdot 6\phi^{(0)} \times 0\cdot 45 = 5\cdot 22\phi^{(0)}$$

with $T_1 = 700°$ K and $T_2 = 1\,020°$ K.

Having presented these results, it must also be recorded that in addition there was a small group of valves, about 30 in all, which could be fitted to the second model only if a very low value of q were assumed. These valves had been given an unsuitable heater and their life-test records showed normal emission characteristics with very serious reductions in g_m (by about 20%) in the first 1 000–2 000 hours' life. The low value of q involved a value of $\phi^{(0)}$ on the lower fringe of, or entirely outside, the distribution of $\phi^{(0)}$ given in Part 1.

A small percentage of the valves (less than 5%) with results presented in Table 1 had increasing values of low-temperature emission for the first few hundred hours of life. During these periods the mutual conductance showed either no change or a slight fall. These periods have been regarded as transients, and the initial values of emission and mutual conductance have been taken at the peak of the emission/time characteristic.

Finally, a short life test was conducted on five valves in which the value of $\phi^{(0)}$ was measured. It was shown here that in the initial stages of life a 50% fall in emission in the region 1–5 mA was due more to the movement of the log $I/(1/T)$ characteristic (RR'R''R''' in Fig. 5) to the left, keeping a substantially constant slope, than to any change of slope or work function. The average value of $\phi^{(0)}$ recorded was 1·15 ± 0·03 volts at each stage.

Table 1

Valve type and life-test conditions	Group	Number of valves	Agreement [eqn. (14)]	q	$\phi^{(0)}$
6P10			%		
$V_a = 250$ volts	(1) Final $(I_s)_{LT} > 100\,\mu$A	130	87	1 000	1·32
$V_{g2} = 250$ volts	(2) Final $(I_s)_{LT} = 80$–$100\,\mu$A	20	97	1 500	1·40
$I_a = 6$ mA	(3) Final $(I_s)_{LT} = 35\,\mu$A	10	98	3 500	1·56
$V_h = 6\cdot 3$ volts					
6P12					
$V_a = 40$ volts	(4) Final $(I_s)_{LT} > 150\,\mu$A	380	87	500	1·19
$V_{g2} = 40$ or 60 volts	(5) Final $(I_s)_{LT} = 100$–$150\,\mu$A	30	86	1 000	1·32
$I_a = 3$ or 4 mA	(6) Final $(I_s)_{LT} = 30$–$50\,\mu$A	30	85	1 500	1·40
$V_h = 5\cdot 5$ volts					
6P12					
$V_a = 90$ volts	(7) Final $(I_s)_{LT} > 150\,\mu$A (Later samples)	160	88	300	1·09
$V_{g2} = 60$ volts	(8) Final $(I_s)_{LT} > 150\,\mu$A (Early samples A)	100	83	400	1·15
$I_a = 6$ mA	(9) Final $(I_s)_{LT} > 150\,\mu$A (Early samples B)	70	87	500	1·19
$V_h = 5\cdot 5$ volts	(10) Final $(I_s)_{LT} < 150\,\mu$A	50	98	800	1·28

(13) DISCUSSION

The bulk of the experimental results given in the previous Section tend to show that the measurements of mutual conductance and low-temperature total emission recorded during life can be aligned with a model of a relationship between the cathode state and the mutual conductance of the valve based on the following four assumptions:

(*a*) That the Langmuir relation for a planar diode can be applied to the equivalent-diode concept of a normal pentode receiving valve.
(*b*) That pentode design data, e.g. those given by Liebmann, give a reasonably close approximation to the valve characteristics, and that the final necessary approximation can be made by assuming that the initial life test values of g_m and normal-temperature total emission locate the model curve, irrespective of non-coincidence of I_a values.
(*c*) That the normal-temperature total emission may be derived from the low-temperature measurement through use of an equation such as eqn. (13).
(*d*) That a resistance is associated with the cathode which has a value given by eqn. (7).

It is considered that assumptions (*a*), (*b*) and (*d*) rest on a much firmer foundation than does (*c*) and that, although the model can be aligned with the experimental results on the basis of the four assumptions taken together, the validity of the alignment must rest on a closer inspection of the assumption (*c*).

Before taking the third assumption in more detail, a comment on the fourth is necessary. The qualitative nature of the interdependence of cathode emission and resistance has a greater weight of supporting evidence than has the quantitative value of the constant of proportionality given in eqn. (7). The figure of 1·6 arises, as explained before, from the work done in Reference 3, and some of the weaknesses of the method have been pointed out. A little extra support comes from the fact that for an emission of 1 amp/cm^2—a figure accepted as representative for oxide-coated-cathodes at 1 000° K—eqn. (7) gives a cathode resistance of 1·6 ohms for a cathode of 1 cm.^{2} This in its turn is acceptable, giving a conductivity of about 4×10^{-3} mho/cm. A still further point to be taken into account is that an increase or decrease in the factor by 50%, i.e. a change to 2·4 or 0·8, would cause the change of q needed to bring the life-test records into line with the model. Such a change in q would involve a change in $\phi^{(0)}$ of about $\pm 0 \cdot 05$ eV at an emission of about 100 μA. These changes could bring the value of $\phi^{(0)}$ for group (4) in Table 1 very close to 1·0 eV and for group (2) to greater than 1·6 eV. As will be shown later, such values are on the limits of acceptable work functions. Any larger changes in the constant in eqn. (7) would involve unacceptable values of $\phi^{(0)}$ if agreement with the second model were required.

Coming now to the third assumption and taking the experimental results in sequence, the graphical comparisons in Figs. 11 and 12 show clearly that, if a q value of 1 000 is used, a model based on the four assumptions gives a better alignment with the life-test records than does a model based on the first three assumptions, at least for emissions less than, say, 750 mA. A q factor of 1 000, giving $\phi^{(0)} = 1 \cdot 32$ eV, corresponds to the centre of the distribution in Part 1 and is thus acceptable as a reasonable assumption. A consequent $\phi^{(5/4)}$ value of 1·2 eV is well within the range of values for the (BaSr)O cathode quoted in recent literature. Herrmann and Wagener[11] give a Table of values of $\phi^{(2)}$ ranging from 1·0 to 1·65 eV obtained by different investigators over the past 30 years. As was mentioned briefly before, in order to force the life-test records into alignment with the first model, very low q values, involving $\phi^{(0)}$ values lower than 1 eV, would be required. These are not obtained in the experimental work in Part 1, nor in the results tabulated by Herrmann and Wagener. Consequently, the first model is rejected for the range of life-test records presented here.

Figs. 11 and 12 also show that the second model apparently breaks down when the low-temperature total emission falls below about 150 μA. It is, however, possible to re-align records and model if it is assumed that the q factor or work function increases when the emission falls below such a level. This concept will be supported during discussion of the Table of life-test results. An increase of work function with reduction of emission is acceptable, being consistent with the general appreciation of the nature of emission from both metals and semi-conductors. Nevertheless it should be noted that the increase of work function, although coinciding with decreasing emission at about 700° K, actually counterbalances the decrease when referring to 1 000° K. This has been noted in extreme cases when running pentodes continuously with anodes at red heat (6 watts in place of the normal 1·5 watts). Here, despite a level of low-temperature emission of about 3 μA, almost completely normal measurements of mutual conductance were made at 1 000° K for the whole period of the test (about 5 000 hours). Without going into detail, these results could be due to balancing changes in the $A^{(n)}$ and $\phi^{(n)}$ factors in eqn. (6), and the present method may provide a way of studying such changes, making use of the large samples available in life-test records.

It must be emphasized that the fact that a constant value of q gives reasonable alignment between model and records for emissions greater than 200 μA cannot stand alone in justifying the hypothesis of a constant work function in this region. It has been pointed out before that, for the higher emission levels, the value of q is not very significant in locating model curves. Hence the alignment of model and records in this region cannot be used to support constancy of q factor, even though a constant q has in fact been used. This is, of course, due to the smoothing effect of the space-change cloud, and is just another way of saying that, for high emission levels, the mutual conductance is largely independent of emission. At the same time it must be remembered that the short life test, where $\phi^{(0)}$ values were measured over a period of time, indicates that there is a possibility of emission changes occurring at these high levels without consequent change in q or $\phi^{(0)}$.

Table 1 will now be considered. The weighted average value of $\phi^{(0)}$ for all the valves is 1·21 eV, and this gives an average agreement of 88% between model and life-test records. The average $\phi^{(0)}$ value for the main part of the distribution in Fig. 7 is 1·35 eV, which corresponds reasonably well considering the increase of 36 times in the size of the sample. The distribution of average $\phi^{(0)}$ values for the 10 groups in the Table ranges from 1·09 to 1·56 eV, and this again is in reasonable agreement with the main distribution and with the Table of values given by Herrmann and Wagener.

Considering the 10 groups in three sets (1)–(3), (4)–(6) and (7)–(10), it will be seen that as the emission falls there is evidence in each set that higher values of q, and therefore of $\phi^{(0)}$, are required to align the model and the records. Remembering again that little significance can be attached to the use of the same q factor for the initial and final results within each group, the results of the three sets give evidence of increasing work functions as soon as the lower emission levels are reached. This is in agreement with the conclusions reached when considering the graphical comparisons in Figs. 11 and 12, and also with the rather slight evidence of increasing work function with life obtained in Part 1.

It will also be observed that for the 6P12 valves the average $\phi^{(0)}$ value is 1·19 eV for group (4) and 1·13 eV for groups (7), (8) and (9), comparing groups with similar final low-temperature emissions but different life-test conditions. In the same way the average $\phi^{(0)}$ value is 1·36 eV for groups (5) and (6) and 1·28 eV for group (10). It would therefore appear that for similar emission levels the work functions necessary to align groups (4)–(6) with the second model are higher than those required to align groups (7)–(10). This is interesting when taken in conjunction with life-test evidence not presented in Section 12. It has been found when life testing higher-quality valves for submarine repeaters that input valves, life tested under the conditions used for groups (4)–(6), always settle down after about 5 000 hours to a low-temperature emission level which is about 70% of that achieved by output valves life tested under the conditions used for groups (7)–(10). The work functions 1·19 and 1·13 eV correspond with q values of 500 and 360. Taking 700 μA as a final figure for the low-temperature emission of higher-quality output valves and 490 μA for similar input valves, these q factors would give estimates of normal-temperature emission of 250 mA for output valves and 245 mA for input valves. Without attaching too much importance to the actual figures, these estimates are more reasonable than the low-temperature levels, since a substantial case can be made to show that the input conditions are less onerous to the cathode state than the output conditions.

There remains to consider that group of valves with unsuitable heaters which could be fitted to the second model only if a very low value of q were assumed. This group bears the same relation to the second model as do the rest of the valves to the first. The medium deteriorations of g_m for the bulk of the valves need very low values of q to produce agreement with the first model. The abnormally high deteriorations of g_m for the group under consideration need, at low emission levels, very low values of q (about 100) to produce agreement with the second model, and absurdly low ones (about 20) for agreement with the first model. The corresponding $\phi^{(0)}$ values are 0·88 and 0·57, both of which are rejected as being unrealistic. These valves also require the peculiar coincidence of a reduction in $\phi^{(0)}$ as the emission decays. Thus, although agreement can be forced, it is preferred to argue that there is a form of deterioration of cathode state which is not in accord with any model proposed here. It could also be argued that failure to fit the second model coincides with a dangerously unsatisfactory cathode state, although successful alignment with the second model does not imply a satisfactory cathode. The behaviour of this group may be contrasted with group (10) in Table 1, whose life-test curve is plotted in Fig. 12 (upper curve). It will be observed that the initial deteriorations in g_m are very comparable, but that the behaviour on subsequent life test is very different. The valves in group (10) are showing signs of complete recovery after more than 20 000 hours, and are also in accord with the second model at all stages of life; the valves in the group under discussion here fail completely before 10 000 hours, and are at no stage in reasonable accord with any model presented here.

Although it is not proposed to suggest any further model at this stage to cover the exceptions in the previous paragraph, it may be useful to indicate one direction in which the solution may lie. Each of the four assumptions on which the second model is based tacitly implies a homogeneous cathode state. It may be that the cause of the deviations lies in non-uniformity of some part of the cathode structure in the presence of particular forms of severe cathode deterioration. This suggestion must, however, await further experimentation before any confidence can be placed in it.

Before leaving this discussion it must be emphasized that all the conclusions reached relate to emission levels lower than about 750 mA. The technique of investigating the relationships between the cathode state and the mutual conductance of the valve, in order to construct a model for the linkage between them, cannot be applied for emissions higher than this level. In such a region changes in emission or in cathode resistance, if inversely proportional to emission, are insufficient to affect the mutual conductance which is used as a yardstick for the whole investigation. Indeed, it will be observed that the first and second models are almost indistinguishable at emission levels greater than 1 amp.

(14) CONCLUSIONS

A method of deriving the normal-temperature zero-field emission from the oxide cathodes of receiving valves was described in Part 1. The method made use of extrapolation from the low-temperature emission measurement and yielded reasonable values of the work function in the process.

The problems of measurement of the cathode resistance of normal receiving valves are by no means solved. It is, however, possible to derive a relationship, based on experiment, between emission and resistance which enables an estimate of the latter to be made in terms of measurements of the former; this necessitates a link between low-temperature and normal-temperature total emission from the cathode, which is established empirically from the work done in Part 1, and introduces the concept of cathode work-function.

The combined effect of cathode emission and cathode resistance can then be used to form a model of the relationship between the cathode state and the 4-terminal mutual conductance of the valve. The model takes account of the current/voltage relationship of a planar diode developed by Langmuir and of valve design data such as those suggested by Liebmann.

The validity of the model is checked first by showing that the life-test records can be manipulated in such a way as to conform with the model, but the real test lies in examining the manipulations which have to be made to produce identity between the model and the records. These manipulations can be reduced to assumptions relating to the cathode work-function, but it can be shown that in nearly all cases these assumptions can be justified through reference to Part 1, or to values of work function accepted in the literature, or to the underlying principles of emission from metals and semi-conductors.

In a limited number of cases the model fails to account for the life-test records because the necessary manipulations of the cathode work-function are unacceptable. The failure may lie in the inhomogeneity of the cathode under certain conditions of severe deterioration of cathode state, but more experimental evidence is required to prove this.

It is hoped that the methods developed may prove useful in permitting the large bulk of evidence amassed in the form of life-test records to be used in attempts to understand the nature of the oxide cathode.

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