APPENDIX

In order to prove Eqs. (39) of the text it is necessary to prove first that every expression $\mathfrak{B}\mathfrak{C}\mathfrak{B}$, where $\mathfrak{C}$ is an arbitrary matrix, is a multiple of $\mathfrak{B}$. This is a consequence of (36a), or, as the mathematicians express it, that $\mathfrak{B}$ is an idempotent of rank 1. We have, in fact

$$(\mathfrak{B}\mathfrak{C}\mathfrak{B})_{kl}=\sum_{jm}\beta_k\beta_j C_{jm}\beta_m\beta_l=(\sum_{jm}\beta_j C_{jm}\beta_m)B_{kl}. \tag{A1}$$

We now can go over to verifying (39). Equation (28) and (32b) give for $\mathfrak{U}$

$$\begin{aligned}\mathfrak{U}=\frac{1+i\mathfrak{u}\mathfrak{S}\mathfrak{u}}{1-i\mathfrak{u}\mathfrak{S}\mathfrak{u}}&=(1+i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u}-ic\mathfrak{u}\mathfrak{B}\mathfrak{u})(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u}+ic\mathfrak{u}\mathfrak{B}\mathfrak{u})^{-1}\\ &=[1+i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u}-ic\mathfrak{u}\mathfrak{B}\mathfrak{u}][(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})\\ &\qquad\times(1+ic(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}\mathfrak{u}\mathfrak{B}\mathfrak{u})]^{-1}\\ &=[1+i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u}-ic\mathfrak{u}\mathfrak{B}\mathfrak{u}][1+ic(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}\mathfrak{u}\mathfrak{B}\mathfrak{u}]^{-1}\\ &\qquad\times(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}.\end{aligned} \tag{A2}$$

For the first factor of this we shall try to write

$$\begin{aligned}1+i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u}-ic\mathfrak{u}\mathfrak{B}\mathfrak{u}&=[1+i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u}-\mu(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}\mathfrak{u}\mathfrak{B}\mathfrak{u}]\\ &\qquad\times[1+ic(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}\mathfrak{u}\mathfrak{B}\mathfrak{u}].\end{aligned} \tag{A3}$$

If this proves to be possible, the product of the first two factors of (A2) will be equal to the first factor on the right side of (A3). We can substitute, by (A1), for the product of the last two terms on the right side of (A3) $-ic\mu\gamma(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}\mathfrak{u}\mathfrak{B}\mathfrak{u}$ with

$$\gamma=\sum_{jm}\beta_j(\mathfrak{u}(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}\mathfrak{u})_{jm}\beta_m. \tag{A4}$$

The right side of (A3) then gives

$$\begin{aligned}1+i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u}+(-\mu+2ic-ic\mu\gamma)(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}\mathfrak{u}\mathfrak{B}\mathfrak{u}\\ +ic(-1+i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}\mathfrak{u}\mathfrak{B}\mathfrak{u}.\end{aligned}$$

This is equal to the left side of (A3) if

$$-\mu+2ic-ic\mu\gamma=0 \tag{A5}$$

or, with (35a) and $c_\infty=0$

$$\mu=\frac{2ic}{1+ic\gamma}=\frac{i\hbar b^2}{E-E_0+\frac{1}{2}i\hbar b^2\gamma}. \tag{A6}$$

With this μ, (A3) becomes an identity. Equation (A2) therefore gives

$$\mathfrak{U}=(1+i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u}-\mu(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}\mathfrak{u}\mathfrak{B}\mathfrak{u})(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}$$

$$\mathfrak{U}=\frac{1+i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u}}{1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u}}-\mu(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}\mathfrak{u}\mathfrak{B}\mathfrak{u}(1-i\mathfrak{u}\mathfrak{S}_\infty\mathfrak{u})^{-1}. \tag{A7}$$

This is indeed equivalent to (39). The λ of (39a) is $\hbar b^2\gamma$.

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The Temperature Dependence of Secondary Electron Emission from Oxide-Coated Cathodes*

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The secondary electron emission from alkaline-earth oxide-coated cathodes has been investigated under both continuous and pulsed bombardment. Experiments have been performed with three types of apparatus. Yield *vs.* energy data reveal values of δ of 4–7 at room temperature, with a more or less flat maximum at approximately 1000 volts primary energy. The yield increases with temperature in an exponential manner, and plots of log $\Delta\delta$ (i.e., $\delta_{K°}-\delta_{300°K}$) *vs.* $1/T$ give straight lines. Values of Q_1 between 0.9–1.5 ev are generally indicated, and from extrapolation of these curves, yields exceeding 100 at 850°C are deduced. The secondary emission depends upon the degree of activation, and increases with enhancement of the thermionic emission characteristics. Short time effects such as growth or decay of secondary current after the onset of primary bombardment or persistence after the cessation of bombardment have not been observed, and values of yield obtained by pulsed methods are in accord with those obtained under d.c. conditions. Tail phenomena reported by J. B. Johnson and interpreted as "enhanced thermionic emission" from oxide-coated cathodes become manifest only under experimental conditions characterized by certain space-charge effects, and have been effectively simulated by bombarding a tantalum target adjacent to an electron-emitting tungsten filament. Various measurements of the energy distribution of secondary electrons as a function of primary voltage and temperature have been obtained. It was observed that the average energy of the secondary electrons decreases with temperature at a rate which more than compensates for the increase in the number of secondaries emitted per incident primary. The mechanism of the observed dependence of yield upon temperature is not well understood. Various alternative explanations are discussed and, in the light of the present state of our knowledge, regarded as untenable.

I. INTRODUCTION

MEASUREMENTS of the secondary electron emission from BaSr oxide-coated cathodes at room temperature have been reported by several investigators.[1] The first suc-

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* This work was done in whole under Contract No. OEMsr-358 between The Franklin Institute of the State of Pennsylvania and the Office of Scientific Research and Development, which assumes no responsibility for the accuracy of the statements contained herein.

[1] K. Sixtus, Ann. d. Physik 3, 1017 (1929); M. Zeigler,

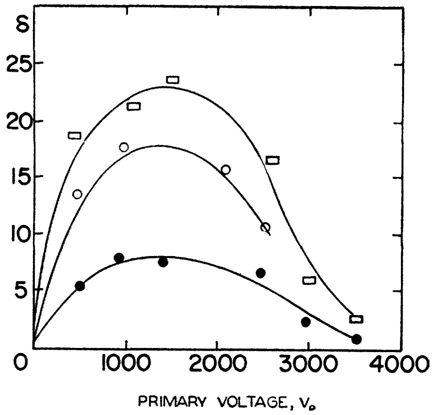

FIG. 1. Secondary electron yield, δ, as a function of primary energy V_p, for an oxide-coated cathode at different temperatures. Tube SE 13. Closed circle, room temperature; open circle, 615°C; open square, 660°C.

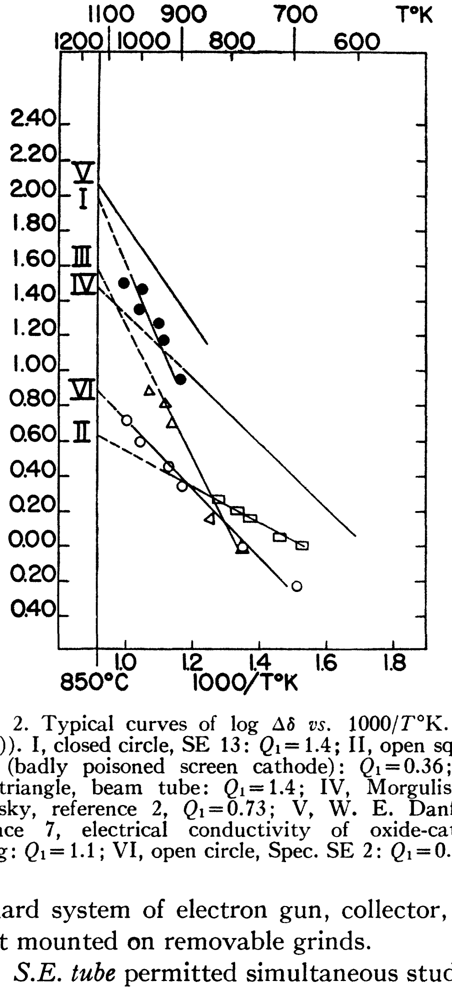

FIG. 2. Typical curves of log Δδ *vs.* 1000/T°K. (See Eq. (1)). I, closed circle, SE 13: $Q_1 = 1.4$; II, open square, SE 3 (badly poisoned screen cathode): $Q_1 = 0.36$; III, open triangle, beam tube: $Q_1 = 1.4$; IV, Morgulis and Nagorsky, reference 2, $Q_1 = 0.73$; V, W. E. Danforth, reference 7, electrical conductivity of oxide-cathode coating: $Q_1 = 1.1$; VI, open circle, Spec. SE 2: $Q_1 = 0.75$.

cessful attempt to study the phenomenon at elevated temperatures was made by Morgulis and Nagorsky,[2] who observed a fivefold increase in the yield at 850°K.

Because of recent developments associated with the attainment of high pulsed thermionic emissions from oxide-coated emitters,[3] it was of interest to examine simultaneously both thermionic and secondary emission characteristics of cathodes prepared under conditions whereby the physical-chemical state of the system requisite for copious pulsed thermionic emission is realized. It was also important to determine whether the secondary emission available in pulses of short duration differs from that under steady-state conditions, as in the case of thermionic emission.

II. APPARATUS AND RESULTS

A. Experimental Tubes

Experiments have been performed with three types of apparatus to be described in detail elsewhere:[4]

(1) *Beam tube* was a demountable continuously-pumped arrangement comprising a more or less standard system of electron gun, collector, and target mounted on removable grinds.

(2) *S.E. tube* permitted simultaneous study of both thermionic and secondary emission properties of oxide-coated cathodes. A movable mounting was provided whereby the specimen cathode could be shifted from its position as target in the secondary electron measuring system into a Kovar-cup anode for diode operation and thermionic emission tests. S.E. tubes were sealed-off after processing.

(3) *Spec. S.E. tube* incorporated special features for the study of transient phenomena. Both pulsed and d.c. measurements were obtained with this apparatus.

B. Steady-State Experiments

1. *Yield vs. Energy*

At room temperature, δ attains a maximum value generally in the range 4–7, at a primary energy of approximately 1000 volts. Figure 1 is

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Physica **3**, 307 (1936); H. Bruining and J. H. DeBoer, Physica **6**, 823 (1939).

[2] N. Morgulis and A. Nagorsky, Tech. Phys. U.S.S.R. **5**, 848 (1938).

[3] M. A. Pomerantz, Proc. I.R.E., in process of publication.

[4] M. A. Pomerantz, J. Frank. Inst., in process of publication.

a typical curve of yield *vs.* primary energy at room temperature, as well as at two higher temperatures.

2. *Yield vs. Temperature*

It is evident that the yield increases with temperature, confirming the earlier results of Morgulis and Nagorsky. Furthermore, if the so-called "anomalous" yield, i.e., the difference between the yield at T°K and that at room temperature, is plotted logarithmically as a function of the reciprocal of the absolute temperature, a straight line is obtained. The dependence is thus of an exponential character, and is represented by the equation

$$\Delta\delta = A \exp\left(-Q_1/2kT\right). \qquad (1)$$

In Fig. 2, typical data obtained in various experiments are plotted in this manner. Because of technical difficulties arising from space-charge effects when thermionic emission from the target becomes excessive, the attainment of reliable measurements at normal cathode operating temperatures (850°C) is precluded. It is consequently necessary to extrapolate data obtained at lower temperatures, a procedure which is justified by available evidence.[4]

TABLE I. Typical secondary emission yield data for oxide-coated cathodes.

Tube No.	Type of coating	Max. yield δ_{max}, at room temperature	Max. extrapolated yield, δ_{max}, at 850°	Pulsed thermionic emission characteristics of cathode: Pulse width = 1 μsec. Rec. freq. = 60 p.p.s.
1	C-51-2 sprayed on grade A Ni	6.7	115	18 amp./cm², emission-limited
5	C-51-2 sprayed on grade A Ni	6.8	110	20 amp./cm², space-charge limited to sparking
9	C-51-2 sprayed on grade A Ni	4.7	Not obs.	27 amp./cm, s.c.l. to sparking
12	C-51-2 sprayed on grade A Ni	3.9	124	20 amp./cm², s.c.l. to sparking
13	Bowie #1 sprayed on Wise #1 Ni	5.7	136	20 amp./cm², s.ç.l.
14	50% MgO, 50% C-51-2 sprayed on grade A Ni	5.8	106	20 amp./cm², s.c.l.
6	C-51-2 painted on 60×60 Ni screen	3.2	54	13 amp./cm², emission limited
3	C-51-2 painted on 60×60 Ni screen	2.7	7	1.7 amp./cm²
		Badly poisoned by diffusion pump oil owing to power failure during bakeout		

C-51-2 is here used to designate a certain commercial Ba-Sr-carbonate coating with an organic binder. Coating densities were generally approximately 10–12 mg/cm².

Table I summarizes some pertinent data obtained with a representative group of S.E. tubes during the optimum phase of the life history of oxide-coated cathodes. The following constitute the essential features:

(a) The yield from a well-activated oxide-coated cathode increases with temperature in an exponential manner and may substantially exceed 100 at 850°C;

(b) In general, the slopes of the curves are of the same magnitude, having Q_1 values of approximately 0.9–1.5 ev.

3. *Yield vs. Degree of Activation*

As a consequence of improved activation techniques, the yields observed have exceeded those reported by others.[1,2] In general, as the degree of activation is improved, the capacity for both thermionic and secondary emission are enhanced, although no quantitative correlation between secondary yield and pulsed thermionic emission has been established. Life test studies have also revealed a qualitative correlation between thermionic and secondary emission characteristics (see Table II).

TABLE II. Life history of an oxide-coated cathode.

Run No.	Pulsed thermionic emission—characteristic of cathode: pulse width = 1 μsec. recur. freq. = 60 p.p.s.	Secondary emission δ	Temp. C°	Aging run
1	Flat at 2 amp./cm²			
2		5.3 55	Room temp. 850°C	
3				17 hr. = 13.5 amp./cm² peaks at end of run: pulse width = 0.9 μsec. rec. freq. = 400 p.p.s.
4	14 amp./cm²			
5		6.4	Room temp.	
6				55 hr. additional, total = 72 hours
7	20 amp./cm² s.c.l.			
8		5.8 106	Room temp. 850°	
9				49 hr. additional, total = 121 hours
10	20 amp./cm² s.c.l.			
11		5.8 86	Room temp. 850°	
12				67 hr. additional, total = 188 hours
13	14 amp./cm² emission limited			
14		4.2 54	Room temp. 850°	Lead burned out

Runs with SE No. 14 are numbered in chronological order.

C. Pulsed Measurements

As a possible explanation of the mechanism responsible for the aforementioned high yields it had been proposed that thin-film field emission,[5] or a modification thereof, might be operative. However, this hypothesis appeared to be inconsistent with available theoretical and experimental data. For example, one fundamental argument against invoking the Malter effect for explaining the high yield from oxide-coated cathodes involves the temperature dependence of the electrical conductivity of this impurity semiconductor. Although it is well known that the resistivity *decreases* with temperature, Malter had demonstrated that in the case of his special films illumination of the surface *reduced* both the high yield and the decay period as a consequence of the lowering of the resistivity by photo-conductivity. Actually, the secondary electron emission from an oxide-coated cathode *increases* with temperature. Nevertheless, in view of the controversial nature of this matter, a direct search for short time effects was undertaken.

Two different experimental arrangements were utilized for the pulsed observations. In the earlier work, measurements with S.E. tubes were extended to times of the order of 10^{-4} sec., whereas the Spec. S.E. tubes were designed for observations in which the primary beam would remain on for intervals in the microsecond range.

In the initial investigations, there was no evidence of growth or decay of the secondary electron emission following application of the bombarding beam, nor was there any indication of persistence and decay of emission following the interruption of the primary beam, with a time constant as low as 10^{-4} sec.

Experiments later performed by J. B. Johnson[6] yielded results which he has ascribed to a new type of electron-emission from oxide-coated thermionic cathodes. This phenomenon manifested itself as an electron current from the target gradually increasing microseconds after the onset of primary bombardment, and a more slowly decreasing current persisting after the abrupt cessation of the bombardment. The effect was described by Johnson as "enhanced thermionic emission excited by electron bombardment." It presumably varied with temperature in about the same way as the steady emission, thus roughly following Richardson's law. It increased with bombardment voltage and current density, and might exceed the steady thermionic current in value. Calculations reveal that the surface temperature rise of the target caused by the bombardment is far too small to explain the increased emission. It was asserted that the effect no doubt explains the exponential rise with temperature previously reported for the yield from oxide-coated cathodes. Johnson concludes from his data that when he subtracts "enhanced thermionic emission" from the total electron current, the secondary emission does not increase with temperature.

The practical importance of ascertaining the magnitude of the secondary emission available in microsecond pulses, as well as the significant theoretical implications of the results of Johnson, stimulated the present attempt to extend the measurements to the 10^{-6} sec. range. The experimental arrangement whereby this has been accomplished will be described in detail in reference 4. Steady-state and pulsed data could be obtained practically simultaneously.

Cathode-ray tube observations revealed that the pulsed secondary emission increases with temperature, just as in the case of d.c. measurements. Furthermore, the yields measured when the primary beam was applied in the form of rectangular microsecond pulses were in good agreement with practically simultaneously-measured steady-state yields at all temperatures from room temperature up to the maximum temperature at which reliable data were available (see Sec. II, B, 2).

When the cathode is heated above some critical temperature, an increase in the amplitude of the secondary emission pulse and a tail (the origin of which will become apparent presently), persisting after the cessation of the primary pulse, begins to appear. It is this phenomenon which Johnson has interpreted as "enhanced thermionic emission." During the present experiments, however, it was observed that the nature of this tail depends quite markedly upon the position of the bombarding beam, which could

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[5] L. Malter, Phys. Rev. **50**, 48 (1936).

[6] J. B. Johnson, Phys. Rev. **66**, 352 (1944).

be caused to scan the surface of the target. This observation was consistent with the expectation that the tail might arise as a consequence of certain instrumental considerations which could be sensitive to the geometry.

The experimental tubes incorporated a feature whereby the target cathode could be moved out of the path of the bombarding beam away from the collector electrode, thereby exposing to the beam a tantalum target with an adjacent helical tungsten filament. It was discovered that upon heating this filament to temperatures at which thermionic emission sets in, an increase in amplitude and a tail on the secondary emission pulse from the tantalum target begins to appear. Its characteristics are similar to those manifested with an oxide-coated cathode as target, and it is particularly significant that *the tail observed with tantalum occurs when the d.c. thermionic emission from the filament is of the same magnitude as that emitted by the oxide-coated cathode targets when the latter manifest tail effects.* This experiment effectively simulates the Johnson effect.

The tail heretofore identified as being attributable to "enhanced thermionic emission" consequently is presumed to arise from purely extraneous causes associated with the presence in the target-collector region of an excessive electronic space-charge. Previously, it had been observed with S.E. tubes that for high target cathode temperatures under d.c. conditions the glass envelope becomes charged, and peculiar growth and decay of currents to the collector occur when the beam is turned on and off, or when the glass is touched. The changes in some instances were of the same magnitude as the initial steady currents. Additional complicated effects of this nature might arise in some instances under conditions of poor vacuum, because of neutralization of some space-charge by positive ion emission from the target produced by bombardment, for example. In fact, any transient disturbance which alters the net d.c. current from target to collector by only an extremely small amount with an appropriate time-constant would result in the appearance of a tail on the target current pulse. In a typical actual case, a rapid variation of microamperes in the steady current to the collector of several milliamperes has been shown to cause the appearance of the tail.

Furthermore, it should be emphasized that the tail phenomenon appears only at those temperatures at which in any event reliable secondary emission measurements are precluded by the considerations already discussed in Section II, B, 2, and hence has not affected the conclusions based upon d.c. measurements. In fact, significant increases in δ already occur prior to the onset of detectable thermionic emission from the target cathode. Therefore, regardless of the exact nature of the effect which causes the short time fluctuation in the steady current from target to collector, the phenomenon must be considered as being not pertinent in discussions regarding the true secondary emission from an oxide-coated cathode. On the contrary, it depends critically upon certain experimental factors including the geometrical disposition of components of the experimental tube, and is a property to be associated with space-charge considerations rather than with the target itself.

III. FACTORS PERTINENT TO THEORY

A. Effect of Coating Resistance

A possible explanation for the increase of yield with temperature might be sought in the electrical conductivity characteristics of the oxide-coated cathode. If the resistance is sufficiently high to cause an appreciable fall of potential in the coating at room temperature, it would be expected that the decrease in resistivity with increase in temperature might enhance the apparent yield. There are several reasons for considering this improbable in the present experiments:

(1) The absence of time effects upon bombardment of targets at room temperature, particularly with microsecond pulses, indicates that the influence of coating resistance is negligible. For high resistances, variations of the secondary current with a time constant RC, where C is the capacitance of the target coating and R its resistance, would be expected to arise.

(2) The resistivity of coatings of this type, prepared according to approximately similar techniques, have been measured by W. E. Danforth[7] using cathodes containing embedded

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[7] W. E. Danforth, OSRD Report, Contract OEMsr-358, Bartol Research Foundation, October 1945, to be published shortly.

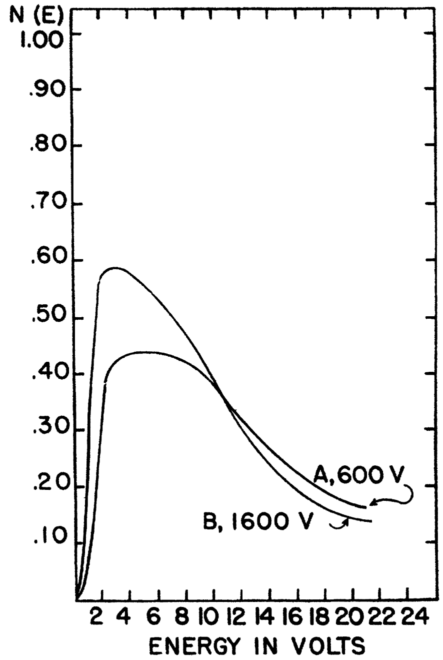

FIG. 3. Energy distribution curves for two primary energies at room temperature. *A*—primary voltage $V_p = 600$ v; *B*—primary voltage $V_p = 1600$ v.

probes. Danforth observed resistances ranging from 50,000 ohms to perhaps as high as 10 megohms occasionally. For the electron currents here involved, the effect of this resistance is negligible. However, it is not difficult to conceive of situations involving cathodes less active than those used here, where the resistance might be considerably higher than the aforementioned upper limit, thereby introducing pulsed effects.

B. Resolution of Dilemma Regarding Conservation of Energy

Difficulty in accounting for the high yields, particularly extrapolated values of 100 secondaries per primary, became apparent in the early stages of the investigation. It seemed impossible to reconcile the observed data with the principle of conservation of energy, if it was assumed that the average energy of the secondaries was even several volts. Consideration of competing processes, preferred directions, solid angles, etc., led to the conclusion that apparently an excessive fraction of the primary energy was manifesting itself as observable secondaries. Studies were therefore undertaken to determine the energy distribution of secondary electrons under various conditions. Where experimental data are comparable, the results are at least in qualitative agreement with those reported by Morgulis and Nagorsky.[2]

The Spec. S.E. tube was particularly well adapted to this phase of the investigation. The measurements were obtained by applying retarding potentials V_c to the collector, and observing the current I_s from the bombarded target to the collector. This provides data for plotting an integral distribution. For any negative value of V_c, the current I_s to the collector is given by:

$$I_s = \int_{V_c^-}^{\infty} N(E)dE, \tag{2}$$

where $N(E)dE$ represents the number of secondaries in the interval dE at E. Differentiation with respect to the lower limit gives the differential energy distribution, or the original function:

$$N(E) = -dI_s/dV_c^-. \tag{3}$$

Secondaries emerging from the target surface into the vacuum in all directions are included in these measurements.

1. Energy Distribution as a Function of Primary Energy

The energy distributions derived from curves of I_s *vs.* V_c^- at two primary voltages, with the cathode at room temperature, appear in Fig. 3. Increasing the bombarding energy results in a shift of the maximum and average energies to lower values. This increase with V_p in the number of slow electrons may be attributed to the greater depth of penetration of primaries, and the subsequent additional energy losses suffered by secondaries which, on the average, must traverse a longer path before emerging from the surface. A change in collision cross section with energy might also be responsible for a shift.

2. Energy Distribution as a Function of Temperature

The energy distributions at room temperature and at two elevated temperatures, for a fixed primary voltage, appear in Fig. 4. It is evident that a considerable change occurs, with a marked shift of the maximum toward lower energies as the temperature is raised. It seems unlikely that the magnitude of this effect is consistent with that expected solely by virtue of the increased amplitude in the thermal vibrations of the lattice and the resulting small additional energy loss per interaction. The difference might be accounted for by the production of tertiaries by the secondary electrons, a process which could also be invoked to account for the increased yields.

The shift in the energy distributions cannot be explained as an experimental consequence of the variation of coating conductivity with temperature. The I_sR_T drop in the target, even at room temperature, was negligible in the present instance. Furthermore, thermionic emission has not been involved in any of the curves, inasmuch as it was still negligibly small compared with secondary emission at the highest temperature cited.

3. *Total Emergent Energies*

The previously mentioned difficulty regarding the conservation of energy is obviated by the decrease in average secondary energy associated with the increase in the yield. The average value of the secondary-electron energy, V_{av}, is obtained from the energy distribution curves of Fig. 4. The mean emergent energy per incident primary is equal to $V_{av}\delta$, and the data summarized in Table III indicate that this total emitted energy at first increases only slightly, if at all, and thereafter even decreases as the temperature is raised.

The yield from the target used in this experiment was lower than those obtained in previous measurements with S.E. tubes. It is therefore necessary to assume that for more active emitters the average secondary energies are even lower than those indicated above. This is tantamount to predicting that the secondary electron energy distribution might vary as a function of the degree of activation of the oxide-coated cathode target. An attempt was made to improve the emitting properties of the target by a treatment involving pulsed aging as a thermionic cathode in the diode position. Unfortunately, only a small but distinct enhancement in emission was thus induced, and although the resulting energy distribution displayed a change exceeding the experimental uncertainty, this effect cannot yet be regarded as having been conclusively established. Further experiments embracing cathodes of widely varying activity should be performed.

TABLE III. Total emergent secondary energy per incident primary.

Temperature, C°	Yield, δ	Mean energy of secondary electron, V_{av}	Mean secondary energy in ev, per 1600 volt primary, $V_{av}\delta$
Room temp.	2.0	11.7	23.4
470	3.1	8.5	26.3
615	5.3	3.7	19.6

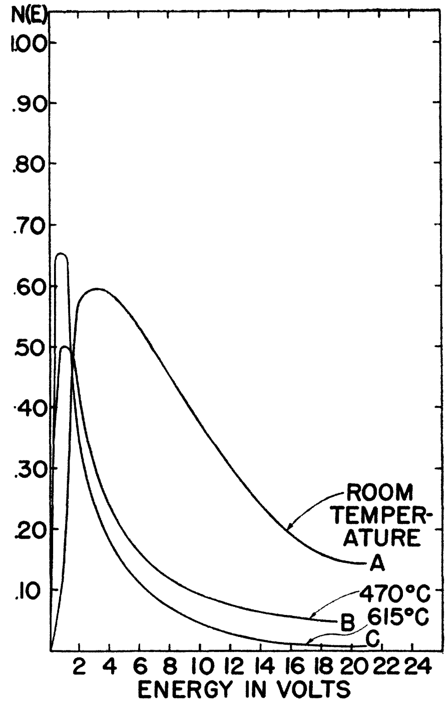

FIG. 4. Energy distribution curves for three temperatures at a constant primary energy $V_p = 1600$ volts. The shapes, but not the relative amplitudes, may be compared. A—room temperature; B—470°C; C—615°C.

C. Mechanism for Temperature Dependence of Yield

The mechanism whereby the secondary electron emission from oxide-coated cathodes increases with temperature is not well understood. An obvious explanation for the additional secondary currents at temperatures higher than the threshold for thermionic emission was sought in terms of local temperature rise of the target surface owing to electron bombardment. Calculations based upon the experimental conditions indicate that this hypothesis is precluded. Johnson[6] has also pointed out that this is far too small to explain the effect. Finally, the increases in yield observed prior to the onset of thermionic emission could not be accounted for in this way.

The similarity between the functional relationship here and in the case of the electrical conductivity (Eq. (1)) appears to be significant. (See Fig. 2, Curve IV). This result might be understood as follows: In general, secondary emission depends directly upon the number of electrons available in the conduction band. In the alkaline-earth oxides, as in other semiconductors, the number of valence electrons is just sufficient to fill an energy band, so that if no excitation occurs, as is the case for low temperatures, no electrons are available for conduction. With increase of temperature, however, thermal excitation to higher-lying bands (conduction bands) occurs. It is these electrons which are responsible for the electronic conductivity of semiconductors at higher temperatures, and which it might be assumed are also available for secondary emission. Quantitatively, the yield *vs.* temperature dependence would then result from the fact that the electronic population in the conduction band is proportional to the Boltzmann factor $\exp[-Q_1/2kT]$ where Q_1 represents the excitation energy,[8] i.e., the energy difference between bands. Thus, provided the work function does not vary sensitively with temperature, and the physical characteristics of the system are preserved as the temperature increases, the yield-dependence upon temperature is given by the corresponding density of conduction electrons.

Theoretical difficulties exist, however. As Fröhlich[9] has pointed out, the laws of conservation of energy and momentum render it improbable that a free (conduction) electron would emerge in the direction from which the primary electron has entered. Thus, only bound electrons are available for secondary emission in the required direction. Furthermore, the number of free electrons in a semiconductor, even at high temperatures, is much smaller than in the case of metals. In any event, it is low compared with the number of bound electrons, which must constitute the main source of secondary emission at lower temperatures. These theoretical difficulties appear to be of a fundamental nature, and probably will be resolved only by the formulation of a new model for the process of secondary emission from an impurity semiconductor of this type.

IV. ACKNOWLEDGMENTS

It is a pleasure to acknowledge valuable assistance rendered by Daniel L. Goldwater during several phases of these investigations. The Cathode Research Group of M.I.T. Radiation Laboratory, with which a valued close collaboration was maintained throughout the course of this project, supplied cathode targets of various descriptions for the present experiments. In the latter connection, appreciation is expressed particularly to E. A. Coomes, J. G. Buck, and A. Fineman.

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[8] Actually the alkaline-earth oxides are impurity semiconductors, the impurity taking the form of free metal (Ba, Ca, or Sr) atoms scattered throughout the oxide. The free atoms provide discrete energy levels which are localized in the forbidden energy region between the filled and conduction bands. The electrons from impurity levels, therefore, require a smaller excitation energy and Q_1 should be identified with this energy required to excite electrons from the impurity level to the conduction band.

[9] H. Fröhlich, *Elektronentheorie der Metalle* (1936), p. 91.