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The Dispenser Cathode

A New Type of Thermionic Cathode for Gaseous Discharge Tubes

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Modern oxide-coated cathodes have the characteristic that the initial high electron emission decreases gradually with time of operation. This characteristic is avoided by using initially-uncoated cathode members to which a coating material is dispensed at uniform rate from a "dispenser" located within the common heat-shield. Such cathodes, after initial aging, show an electron emission equal to the initial emission of oxide-coated cathodes, which does not decrease with time. In the cathodes which have been tested, the dispenser was a closely woven "stocking" of fine molybdenum wires, filled with granules of fused $BaO-Al_2O_3$ eutectic. It was maintained at 1150° C by current through it, and served as a radiation heater for the cathode. The electron-emitting members were clean molybdenum. These cathodes show undiminished electron emission at the end of three years life test with no indication of exhaustion.

1. Introduction

MODERN oxide-coated cathodes consist of nickel or platinum-nickel base to which the coating of barium and strontium oxides is applied once-for-all by means of a spray or dip. They represent the most efficient and most durable type of cathode in use today. Yet they have certain unfavorable features for heavy current tubes (above 25 amperes). The coating tends to flake off when applied to large areas, especially in the presence of mercury vapor. Its high electric resistance causes it to be heated by the emission current;[1] or to be electrolyzed, with liberation of oxygen.[2] It must be "activated," by chemical reaction with reducing elements in the base metal,[3] or with carbon deposited from the vapor phase,[4] or by electrolysis. It gradually evaporates, limiting the life of the cathode.[5] Long life has been attained under certain conditions,[6] though much remains still to be learned regarding the maintenance of emission during life.

2. Structure of Dispenser Cathode

The dispenser cathode is similar to the heat-shielded oxide-coated cathode,[6] except in the method of applying the coating; the coating material is dispensed to the cathode members gradually and continuously throughout life, instead of being applied all at once. Fig. 1 shows the structure of a typical dispenser cathode. It differs from the oxide-coated cathode in two respects: (1) The electron-emitting members, in this case radial vanes, are clean molybdenum, instead of oxide-coated nickel. (2) The tungsten filamentary heater is replaced by a porous tubular filament, filled with activating material, which serves both as heater and as "dispenser" of coating.

The tubular filament may be a closely-wound helix of tungsten or molybdenum wire, or a tube of perforated molybdenum foil. But the most convenient form is a closely-woven cylindrical mesh or "stocking" of fine molybdenum wires, as shown in Fig. 1. It is easy to choose the dimensions of the stocking so that its voltage and current at the desired temperature are the same as those of the corresponding tungsten heater, thus making the dispenser cathodes interchangeable with oxide-coated cathodes. For example, a closely-woven stocking of 3-mil (0.075 mm) molybdenum wire, 2 mm in diameter and 20 cm long, requires 20 amperes at 5 volts to maintain its temperature at 1150°C in an enclosure at 850°C. Fig. 2 shows a cathode with such a dispenser, mounted in a tube of standard form.

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[1] W. Espe, Zeits. f. tech. Physik **10**, 493 (1929).
[2] J. A. Becker, Phys. Rev. **34**, 1323 (1929).
[3] M. Benjamin, Phil. Mag. **20**, 1 (1935).
[4] C. H. Prescott, Jr. and J. Morrison, J. Am. Chem. Soc. **60**, 3047 (1938).
[5] M. Benjamin and H. P. Rooksby, Phil. Mag. **15**, 810 (1933); Claassen and Veenemans, Zeits. f. Physik **80**, 342 (1933).
[6] A. W. Hull, Trans. A. I. E. E. **47**, 753 (1928).

As "activating" filler for the dispenser we have used barium oxide in the form of small granules of fused Barya-alumina eutectic (70 BaO, 30 Al_2O_3 by weight). In this eutectic the free barium oxide is so well protected that the granules can be kept in air for years, without deterioration. On the other hand, the rate of diffusion of BaO at 1150°C is sufficient to build up nearly equilibrium pressure of BaO inside the stocking, thus insuring a constant rate of supply of BaO, and of its reaction products with Mo, to the cathode members, as long as any barium oxide remains inside the stocking. This constancy of dispensing rate makes possible the constant electron emission throughout life, which is characteristic of dispenser cathodes.

The optimum value of porosity of the dispenser is that which supplies active material at just the right rate when the dispenser is at the required temperature, *viz.*, the temperature at which it reacts with BaO to give the required active product. In the case of Mo this temperature is between 1150° and 1200°C. The desired rate of dispensing is the rate just equal to that at which the coating is lost by evaporation from the cathode surface. The chemical tests given in Table VI show an accumulation of BaO on the cathode surfaces, indicating that the dispensing rate was higher than necessary. The porosity in this case was approximately 0.001, as evidenced by the ratio of the observed evaporation to the calculated value for a free surface.

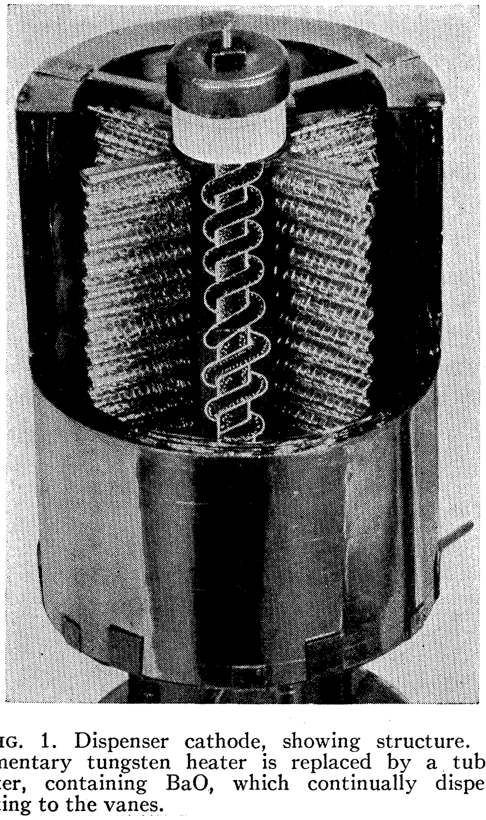

FIG. 1. Dispenser cathode, showing structure. The filamentary tungsten heater is replaced by a tubular heater, containing BaO, which continually dispenses coating to the vanes.

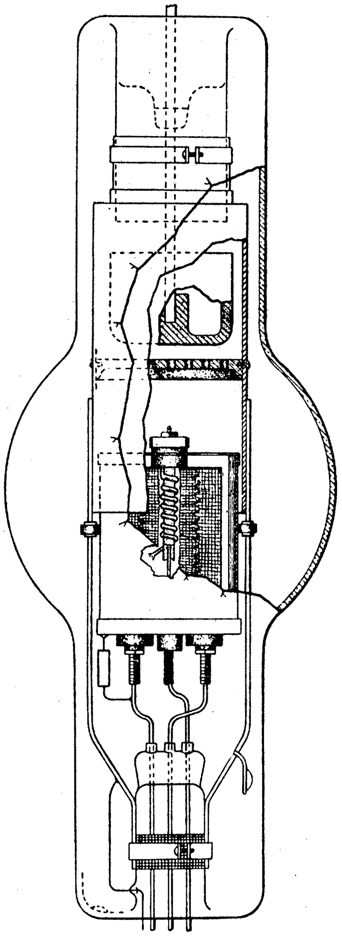

FIG. 2. Thyratron embodying dispenser cathode of Fig. 1.

Figure 3 shows an alternative form of cathode, in which the same stocking is compressed axially to form a straight tube, which is mounted axially in the cathode. The volt-ampere characteristics of a given stocking are approximately the same when thus compressed as in the extended form of Fig. 1. An experimental tube embodying this cathode is shown in Fig. 4.

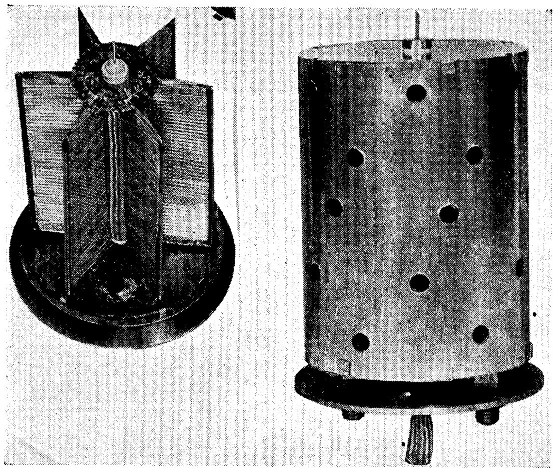

FIG. 3. Cathode embodying alternative form of dispenser. The molybdenum "stocking" is compressed to form a straight tube.

3. ELECTRON EMISSION

A number of tubes of the form shown in Fig. 2 have been built and tested. The electron-emitting vanes are molybdenum foil, 3 mils (0.075 mm) thick, to which molybdenum gauze has been welded on both sides, to increase the surface, giving a total surface area of 200 cm^2. The heat shield is insulated and plays no part in the emission; but it serves the important function of distributing the coating material, by re-evaporation, in addition to conserving heat and coating material.

Table I gives the electron emission of one of these tubes after 1000 hours of operation. The cathode in this tube was equipped with a platinum to platinum -10 percent rhodium thermocouple, whose junction was welded to the center of one of the vanes. Previous tests in a bell jar had shown that the average temperature thus determined represented all parts of the cathode, except the very lowest portions which were cooled by the supports, within about 10°C.

The method of determining the emission needs explanation: Since the currents are large enough to change the temperature of the vanes, it is necessary to make instantaneous observations. This is done by sending a single half-cycle of alternating current through the tube, and observing the voltage drop with a cathode-ray oscillograph. This drop has a "flat" constant value of about 15 volts for small currents; for larger currents it rises slightly in the middle of the cycle, representing the added drop necessary to extract electrons from the deeper portions of the cathode. When the emission limit is reached, an instantaneous demand for more emission causes the drop to increase abruptly. It is this limit, or a value just short of it, which is determined.

In Fig. 5 this limiting value of emission is shown recorded by a magnetic oscillograph, for the same tube at two temperatures; and these values are included in Table I and shown in Fig. 8. The method of taking these oscillograms was, first, to find the limit as described above, and adjust the circuit resistance; then, after waiting several minutes for the temperature to become constant, make the potentiometer reading of the thermocouple voltage, giving the temperature at the center of the vanes; then close the circuit and trip the oscillograph shutter in as close succession as possible. It was estimated that the oscillograph record began about 3 cycles after the current started, and that the maximum change in temperature before recording was 2°C.

The electron emission shown in Fig. 5 for the dispenser cathode can be judged most easily by comparison with oxide cathodes. Traces (c) and (d) of Fig. 5 show a similar test of an oxide cathode of standard type, which has a very high initial emission. This tube also was equipped with a thermocouple. The test was made with the tube in its initial condition, after the customary 24 hours aging. Trace (d) shows a current

TABLE I. *Electron emission tests of tubes similar to Fig. 2, with oxide cathode and dispenser cathode, respectively.*

TYPE OF CATHODE	CATHODE TEMP. °C	CATHODE WATTS	Hg PRESSURE, MM	ELECTRON EMISSION AMP.	AMP./CM^2	AMP./WATT
Dispenser (data from oscillograms, Fig. 5)	714	60	0.014	45	0.225	0.75
	786	72	0.030	355	1.77	4.9
Dispenser (cathode-ray oscillograph tests)	734	63	0.021	107	0.53	1.70
	785	72	0.027	225	1.22	3.12
	831	80	0.023	360	1.80	4.50
Oxide (data from oscillograms, Fig. 5)	831	90	0.012	211	1.17	2.33

just less, trace (c) just greater, than the limit. The sudden drop in voltage at the middle of the cycle in trace (c) evidences the formation of a "cathode spot" on the oxide surface, indicating that the emission limit was exceeded.

Similar tests were made on the tube shown in Fig. 4, which was likewise equipped with a Pt-Pt Rh thermocouple, welded to the center of one vane, and carefully shielded. In this case an automatic timing device was employed to insure a duration of current of only one half-cycle. The data are given in Table II. The cathode was not yet fully activated, having been "aged" for a few hours with 40 amperes emission.

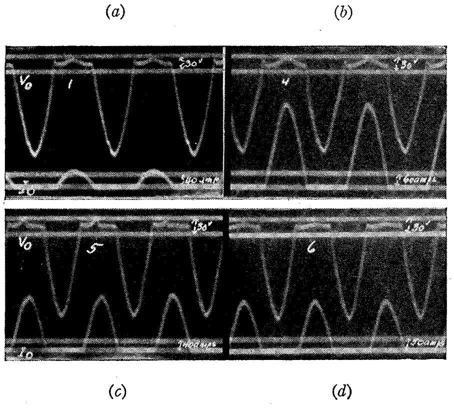

FIG. 5. Oscillograms of current and voltage drop of tubes similar to Fig. 2. The zero lines of the voltage and current traces are indicated by V_0 and I_0, respectively. Direct-current calibrations are shown at 30 volts and 40–60 amperes. (a) Dispenser-cathode tube, cathode temperature 714°C. (b) Same, cathode temperature 786°C. The current at middle of cycle is 355 amperes. (c) Oxide cathode tube, cathode temperature 835°C. The break at middle of cycle shows formation of cathode spot. (d) Same, slightly smaller current. Current at middle of cycle 211 amperes.

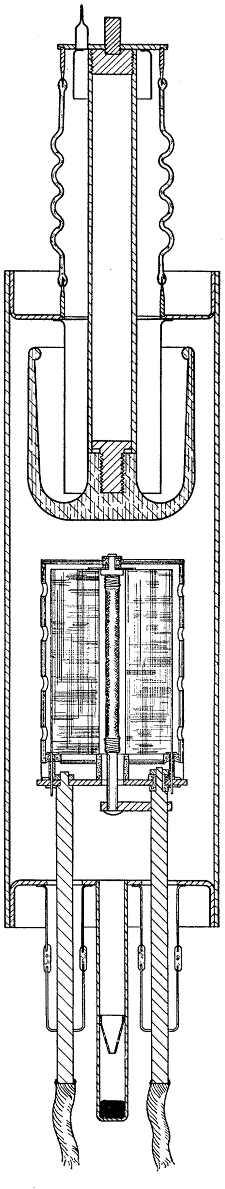

FIG. 4. Rectifier tube embodying cathode of Fig. 3.

4. RICHARDSON CONSTANTS OF DISPENSER CATHODE

The practical forms of cathode described above are not suitable for determination of the electron-emission constants. The special cathode used for this purpose is shown in Fig. 6. The cathode proper is a massive molybdenum cylinder, 1.5 mm thick, 1.90 cm internal diameter and 1.50 cm long, to the outside of which is welded a Pt-Pt Rh thermojunction. Inside of this cylinder is mounted a molybdenum dispenser tube filled with $70\text{BaO}+30\text{Al}_2\text{O}_3$ granules, as described in Section 2. Radiation shields, at each end of the cylinder, were supported on the dispenser mount and served, with it, as anode for the electron currents. The tube was degassed, filled with neon at 2 mm pressure, and sealed off. Activation was accomplished by passing a current of 1 to 5 amperes at 15 volts from the cylinder, as cathode, to the dispenser and end plates, as anode, for a total of six hours.

Emission tests were made at 17 volts, in order to avoid ionization of the neon; hence the emission which was measured is essentially "field-free" emission. A space-charge test at one milliampere showed six-percent change in current for 25-percent change in voltage. The maximum current used for the emission tests was 470 microamperes.

The results of the emission tests are given in Table III and Fig. 7. All the readings, which were taken on five different days, have been included, in order to show the remarkable constancy of the emission. It will be seen that only two readings deviate from the common straight line by more than the experimental error, ±1°C, of the temperature measurements.

The data in Fig. 7 yield the constants, in the Richardson equation:

$$A = 0.85 \text{ amp./cm}^2/\text{deg}^2.$$
$$\varphi = 1.215 \text{ electron volts.}$$

For convenience of comparison, the emission represented by these constants in the range of practical operating temperatures has been plotted in Fig. 8, together with the best available data on oxide-coated cathodes.

5. LIFE

The most important feature of the dispenser cathode is its maintenance of electron emission during life. Life tests were made on small tubes of the form shown in Fig. 9. The results to date are given in Table IV. This table contains all the tubes of this type* that were tested, and it will be noted that all except two are still operating; one failed after 14,173 hours from an unrecorded cause, the other was broken by accident during test, after 23,850 hours.

TABLE II. *Electron emission of cathode shown in Fig. 4, after initial aging.*

CATHODE TEMP. °C	CATHODE WATTS	Hg PRESSURE MM	ELECTRON EMISSION		
			AMP.	AMP./CM²	AMP./WATT
691	300	0.020	120	0.080	0.40
738	365	0.022	240	0.160	0.61
788	450	0.030	520	0.350	1.26
838	545	0.033	730	0.49	1.34
845	560	0.011	760	0.51	1.36
888	660	0.035	1080	0.73	1.64
930	780	0.025	1400	0.94	1.80

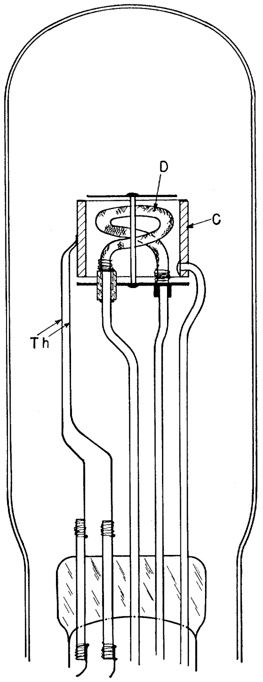

FIG. 6. Special dispenser cathode used for study of electron emission constants. C = cathode; D = dispenser; Th = thermocouple. The massive form is designed to give uniform temperature and enable use of thermocouple.

One of these tubes, No. 35879, was retested on April 12, 1939, after approximately 30,000 hours operation. The results are given in Table V, and are shown on curve 1 in Fig. 8. The emission tests were made by instantaneous observation of current and voltage drop, with the aid of the cathode-ray oscillograph, as already described in connection with the data of Table I. The cathode temperatures were determined by optical pyrometry as follows: Pyrometer measurements on three clean tubes, duplicates of the tube under test, gave identical temperatures within 10°C for the same watts. One of these was then carefully pyrometered, determining temperature as a function of watts. These readings, converted to true temperatures by correction for emissivity and glass absorption, fitted well on a log W *vs.* 4 log T straight line plot. This plot was used to convert watts to temperature for tube 35879, which was too black for observation. The results are believed to be trustworthy within 20°C. Correction has been made for the emission of the dispenser itself (connected to cathode in 35879), by determining the emission from the dispenser of a simi-

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* These tubes all contained mercury vapor. Some tubes containing neon were tested also, but the heating of the cathode by the neon discharge, and the tendency of the neon to clean up, make the results less definite.

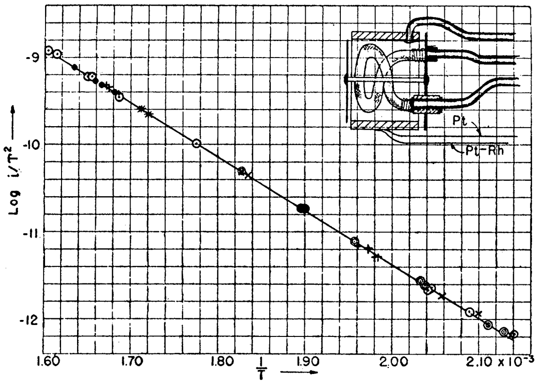

FIG. 7. Richardson plot of emission from dispenser cathode, of 20 cm² area, measured at 17 volts. The plot includes data taken on five different days (distinguished by different symbols). It is represented by the equation $i=0.85\ T^2e^{-1.215/kT}$ amp./cm² (k = Boltzmann constant in electron volts $=8.62\times10^{-5}$).

TABLE III. *Electron emission of dispenser cathode.*

DATE	THERMOCOUPLE READING		ELECTRON EMISSION		
	MILLIVOLT	TEMP. °K	MICROAMPERE	$1000/T$	$\log_{10} i/T^2$
Mar. 27	2.67	612	285	1.634	0.881−10
	2.59	603	198	1.658	0.736−10
	2.56	600	170	1.667	0.674−10
	2.51	595	140	1.681	0.597−10
Mar. 28	2.42	584	90	1.712	0.421−10
	2.39	581	73	1.721	0.335−10
Apr. 3	2.50	593	127	1.686	0.558−10
	2.55	598	172	1.672	0.682−10
	2.54	597	166	1.675	0.668−10
	1.715	505	1.30	1.980	0.707−12
	1.70	504	1.295	1.984	0.707−12
	1.73	507	1.66	1.972	0.810−12
	1.75	510	1.79	1.961	0.838−12
	1.73	507	1.625	1.972	0.801−12
	1.58	490	0.524	2.041	0.339−12
	1.55	486	0.426	2.058	0.256−12
	1.485	476	0.262	2.101	0.063−12
	1.395	468	0.141	2.137	0.809−13
	2.065	545	12.95	1.835	0.641−11
	2.08	547	14.3	1.828	0.679−11
Apr. 4	1.834	467	0.151	2.141	0.840−13
	1.484	479	0.271	2.088	0.072−12
	1.333	461	0.095	2.169	0.650−13
	1.573	489	0.546	2.045	0.359−12
	1.90	527	5.14	1.898	0.267−11
	2.223	563	32.2	1.776	0.007−10
	2.62	606	220	1.650	0.777−10
	2.75	620	404	1.613	0.022−9
	2.79	624	470	1.603	0.082−9
	2.615	605	223	1.653	0.785−10
	2.495	593	123	1.686	0.544−10
Apr. 6	1.41	470	0.165	2.128	0.873−13
	1.44	474	0.194	2.110	0.936−13
	1.59	491	0.59	2.037	0.390−12
	1.60	492	0.64	2.033	0.422−12
	1.76	511	2.07	1.957	0.899−12
	1.90	527	4.8	1.898	0.239−11
	1.91	528	5.1	1.894	0.262−11
	2.08	547	15.3	1.828	0.708−11

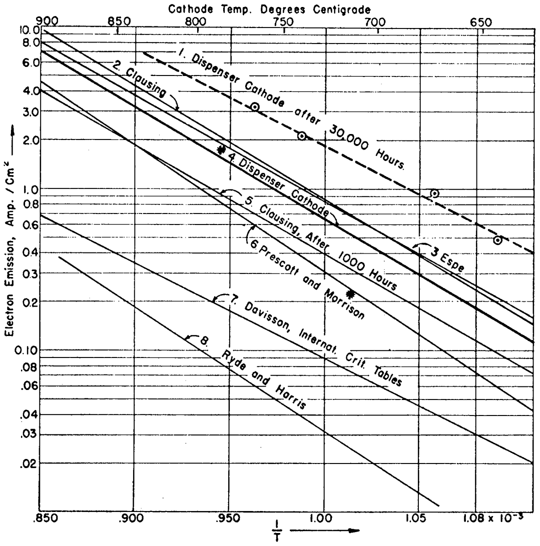

FIG. 8.

1. Dispenser-cathode, after 30,000 hours operation (See Table V).
2. P. Clausing;[7] "well activated" nickel filament, coated with BaO+SrO: $A=0.96$, $\varphi=1.20$.
3. W. Espe, reference 1; barium on oxidized tungsten: $A=0.3$, $\varphi=1.10$.
4. Dispenser-cathode (from data of Table III and Fig. 7): $A=0.85$, $\varphi=1.215$.
5. P. Clausing, same as 2, after 1000 hours operation: $A=0.25$, $\varphi=1.15$.
6. Prescott and Morrison, reference 4; Pt-Ni, coated with BaO+SrO and activated by C from CH_4: $A=2.45$, $\varphi=1.37$.
7. *International Critical Tables;* Pt-Ni, coated with BaO+SrO (data from Bell Laboratories): $A=10^{-2}$, $\varphi=1.0$.
8. Ryde and Harris;[8] Ba-O-W: $A=0.18$, $\varphi=1.34$.

lar tube with insulated dispenser, which had been operated for the same length of time. This correction, approximately three percent, was subtracted from the observed emission of tube 35879. The data in Table V and Fig. 8, thus corrected, represent the emission from the molybdenum cup.

This emission is quite high, and would still be high if one allowed for a possible error of 20° or even 30° in temperature. The measurements of current and temperature are not accurate enough to justify derivation of Richardson constants, but they justify the conclusion that the electron emission of this cathode, after 30,000 hours of life-test operation, is higher than any initial emission that has been observed.

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* Dispenser-cathode after 1000 hours, from oscillogram, Fig. 5.

[7] P. Clausing, unpublished data, quoted by J. H. DeBoer, *Electron Emission and Absorption Phenomena* (MacMillan, 1935), p. 361.

[8] J. W. Ryde and N. L. Harris, unpublished data, quoted by A. L. Reimann, *Thermionic Emission* (Chapman and Hall, London, 1934), p. 165.

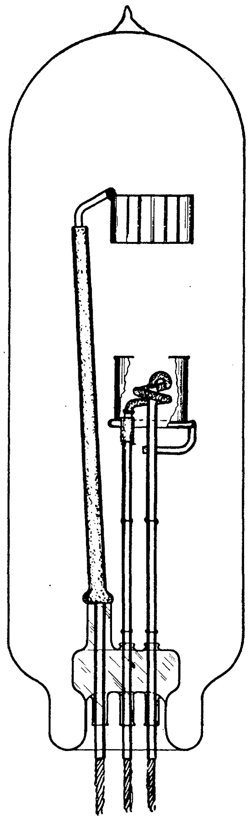

FIG. 9. Dispenser-cathode tube used for life tests. The dispenser is the same as in Fig. 1.

In applying the results of these life tests to practical cathodes for heavy current tubes like that shown in Fig. 1, one may proceed with considerable confidence. If the temperatures of dispenser and cathode enclosure are the same in the two cases, and also the ratio of dispenser area to cathode opening, then one may expect the same density and vapor pressure of active material, and hence the same electron emission per unit of cathode surface throughout life.

What is the limit of life of a dispenser cathode? The data in Table VI give some information on this subject. These data show that less than half of the barium oxide left the "stocking" in 20,000 hours, and half of this was still in the cathode enclosure. Only one of these tubes (No. 35168, broken during test) contained mercury vapor. This tube shows a net loss of BaO from the cathode enclosure of only 7 mg, or 2.4 percent, in 23,850 hours, which would indicate a possible life of many years. The neon tubes ran about 50° hotter, on account of the high ionization energy of neon, which accounts for their greater evaporation. However, the initial amount of activating material in the dispenser is not limited; hence a very long life appears possible under any reasonable operating conditions, by proper design. Perhaps the most important consideration, if these data are substantiated by further tests, will be the ability to predict life, from the amount of material in the dispenser and the rate of dispensing.

TABLE IV. *Life tests of barium-dispenser cathodes.*

	Life Tests Conditions				Electron Emission 11/20/38	
Tube Number	Mercury Temperature deg. C	Cathode Watts	Anode Current Amperes	Hours Operation at 11/20/38	at 770°, amp.	Hg 40°C amp./cm²
35036	<40	53	3.0 d.c.	31334+	22	1.1
34743	60	47	9.5 max. a.c.	32178+	12.6	0.63
35907	40–50	47	5.7 “	26279+	25	1.25
35867	40–50	47	5.7 “	26279+	25	1.25
35879	40–50	47	8.8 “	26279+	70	3.5
35933	40–50	47	9.5 “	14173	—	—
36593	30	45	9.5 “	19368+	39	1.95
35168	75	47	13.5 “	23850	*	*
35181	75	47	20.5 “	27980+	12.6	0.63
35174	72	47	7.9 “	27980+	25	1.25
35082	80	47	13.2 “	23850+	12.3	0.61
			Ave.	25414+	27.0	1.35

* Broken during test; used for chemical analysis.

TABLE V. *Electron emission of experimental dispenser cathode after 30,000 hours operation.*

Cathode Temp. °C	Cathode Watts	Hg Pressure mm	Electron Emission amp.	Electron Emission amp./cm²
597	18.8	0.012	2.0	0.10
644	25.5	0.012	10.0	0.50
672	30.3	0.0155	18.9	0.95
740	44.0	0.010	43.1	2.15
766	50.5	0.0165	64.2	3.21

TABLE VI. *Distribution of barium oxide in dispenser-cathode tubes.*

			Milligrams of BaO				
Tube Number	Hours of Operation	Gas	Stocking	Cup	Bulb	Anode	Total
35168	23,850	Hg	242.5	43.8	7.0	0.0	293.3
34932	19,044	Ne	135.3	50.3	4.4	0.0	190.0
34949	21,644	Ne	97.8	43.8	32.7	12.8	187.1
34977	20,181	Ne	103.3	63	37.4	16.8	220.6
blank	0*	Ne	191.5	—	—	—	191.5

* New tube.

In contemplating long operating life the question of vacuum deserves consideration. Some observations were made last year on power Thyratrons which had been in operation for two years at constant current (175 amperes, 120 degree conduction). These tubes were tested in the laboratory for ability to operate at high voltage, and the results compared to initial tests on the same tubes. In every case the voltage tolerance was found to be higher than at the start. This shows that vacuum is not impaired by operation under these conditions.

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Change of Resistance in a Magnetic Field

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The general theory of the Hall effect and the change of resistance in a magnetic field expresses these quantities in terms of a number of integrals over the surface of the Fermi distribution. The values of these integrals depend upon the form of the electron energy and the relaxation time as functions of the wave vector. If the free electron situation is assumed, the Hall effect has the right order of magnitude, but there is no change of resistance. This can be seen from a qualitative consideration of the effect of the fields on the distribution function. A general form for the functions in other cases can be obtained as an expansion in spherical harmonics with the symmetry of the crystal lattice. The results can then be expressed in terms of the coefficients in this expansion. When only the first two harmonics are retained, the computed change of resistance and Hall effect are close to the observed values. However, contrary to the available observations, the ratio of the transverse to the longitudinal change of resistance shows a minimum value of about four. It seems improbable that this result could be changed in any material way by the inclusion of higher series members, so that if the experimental results are to be taken as reliable, doubt is thrown on the general method of treatment.

§1. INTRODUCTION

CHANGE of resistance in a magnetic field cannot be interpreted in terms of a free electron picture. But since such a change is observed in the alkalies, it is of interest to see if it can be understood as a small departure from the free electron situation. Jones and Zener[1] have given a theory for this effect that seems to give quite satisfactory numerical results in the case of lithium. However, their approximate method of evaluating the integrals made it necessary to apply, later, an estimated correction factor of about six. This paper attempts to give a method of evaluating the integrals that will enable one to get analytically as good an approximation as is desired, provided the surfaces of constant energy are not too irregular. Also it is not assumed that the relaxation time is a function of the energy only. §2 gives a summary of the general theory, in Wilson's[2] notation, and §3 gives a physical picture of the situation, in which particular attention is given to the free electron case. In §4 the energy and the relaxation time are expressed in terms of series of cubically symmetric spherical harmonics. By a proper choice of independent variables, the integrals can all be evaluated in terms of the coefficients of the spherical harmonics. If the first two terms of the series are taken as a satisfactory approximation, expressions are obtained for the conductivity, the Hall coefficient, and the two coefficients, B_t and B_l, of the change of resistance in a magnetic field. In §5 the conclusions that may be drawn from these expressions are discussed. It is found that theory and experiment give radically different values of B_t/B_l. Experimentally this ratio is about unity, while no choice of parameters can give a theoretical value less than 4. The expressions for B_t and B_l show that the variation of the

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[1] H. Jones and C. Zener, Proc. Roy. Soc. **A145**, 268 (1934).

[2] A. H. Wilson, *The Theory of Metals* (Cambridge Univ. Press, 1937), Chapter V.

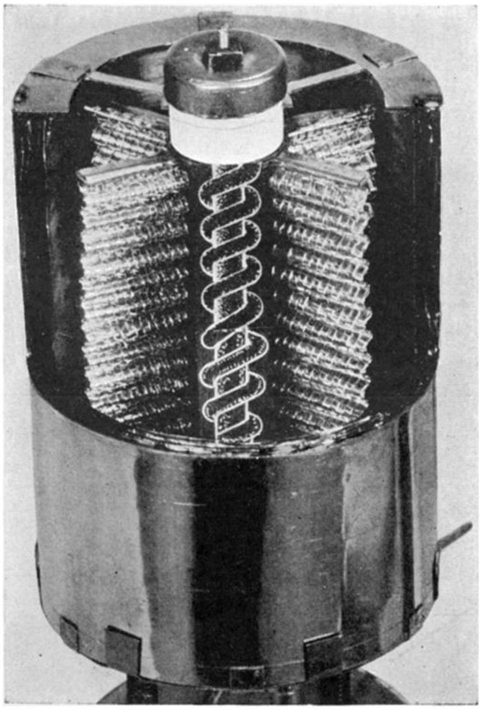

FIG. 1. Dispenser cathode, showing structure. The filamentary tungsten heater is replaced by a tubular heater, containing BaO, which continually dispenses coating to the vanes.

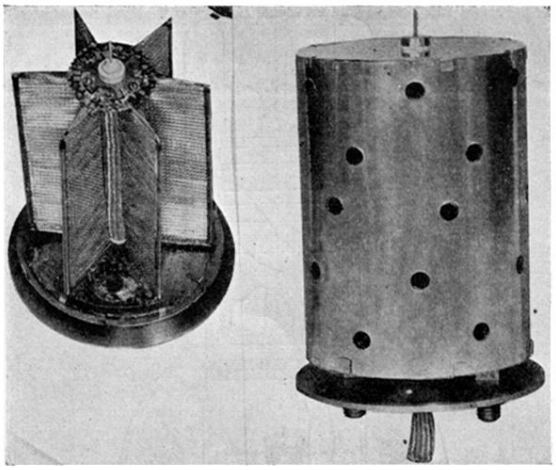

FIG. 3. Cathode embodying alternative form of dispenser. The molybdenum "stocking" is compressed to form a straight tube.

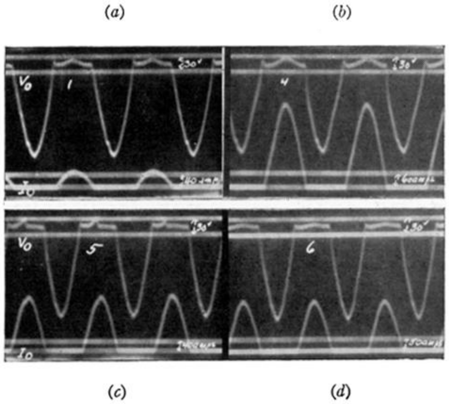

FIG. 5. Oscillograms of current and voltage drop of tubes similar to Fig. 2. The zero lines of the voltage and current traces are indicated by V_0 and I_0, respectively. Direct-current calibrations are shown at 30 volts and 40–60 amperes. (a) Dispenser-cathode tube, cathode temperature 714°C. (b) Same, cathode temperature 786°C. The current at middle of cycle is 355 amperes. (c) Oxide cathode tube, cathode temperature 835°C. The break at middle of cycle shows formation of cathode spot. (d) Same, slightly smaller current. Current at middle of cycle 211 amperes.