The L-Cathode Structure*

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***Summary*—A new dispenser-type emitter, known as the L cathode, is described and compared with three common types of emitters. A discussion of the methods of measuring the rate of barium evaporation is included, as well as the life performance of the L cathode in a number of diversified types of electron tubes.**

INTRODUCTION

THIS PAPER is concerned with a high-emission density thermionic emission cathode known as the L cathode and described in the *Philips Technical Review*, June, 1950, by Messrs. Lemmens, Jansen, and Loosjes.

We will briefly review some of the basic features of this cathode and report some recent progress in its development.

In existing commercial tubes now available, three types of cathodes are being widely used, namely, the oxide-coated cathode, the thoriated tungsten cathode, and tungsten cathodes. The oxide-coated cathode having the best thermal efficiency and requiring the least heating power for a given electronic emission has been widely used in receiving tubes. Its undesirable properties are susceptibility to poisoning through traces of oxygen or other gases, and evaporation of barium causing grids and anodes to emit electrons. For transmitting and X-ray tubes, barium evaporation is very objectionable. In addition, these types of tubes require a cathode capable of withstanding the electrostatic forces of attraction of the anode, which is at a high potential. Oxide-coated cathode coatings peel or are pulled off by these strong electrostatic forces. For these applications, thoriated tungsten and tungsten cathodes are usually preferred.

In microwave tubes, none of the above types of cathodes displays all the desired properties of high-emission density, freedom from damage by sparking, ability to withstand the electrostatic forces of the anode, and poisoning effects of gases or vapors that result from operating the tube. Some improvements have been made in oxide-coated cathodes by reinforcing the oxide coatings with metal, as is accomplished in mesh-and "mush"-type constructions.

The L cathode, the development of which was started at the Philips Laboratories in Eindhoven, overcomes the difficulties of the above-mentioned cathodes. Its great mechanical strength, combined with high-emission density, long life, high resistivity against poisoning, and low noise characteristics, should render it suitable for a large number of tube applications.

Before considering the mechanical structure of the L cathode, we will briefly summarize the properties of the cathodes mentioned.

In Table I we note the emission capabilities of the most generally accepted cathodes used in commercially available electron tubes. In order of emission per square centimeter, the tungsten cathode has the lowest yield, and the L cathode indicates the greatest yield, particularly under dc conditions. As for efficiency, expressed in amperes per watt, the oxide cathode appeared most efficient under pulsed conditions, while the L cathode is best under dc conditions. In comparison to oxide-coated cathodes, the L cathode excels in its resistance to poisoning, to high-voltage electrostatic field, and to high-speed gas ions.

TABLE I[1]

	Maximum Useful Thermionic Emission A/cm²	*Maximum Useful Thermionic Yield A/watt*	*Poisonability*	*Resistance to High Voltage*	*Resistance to High Speed Gas Ions*
Tungsten —dc	1	0.006	Small	Good	Good
Tungsten —pulsed					
Thoriated W —dc	2	0.070	Large	Good	Poor
Thoriated W —pulsed					
Oxide cathode —dc	0.5	0.25	Large	Poor	(Good for a short time)
Oxide cathode —pulsed	50	20.00	Large	Fair	
L Cathode —dc	300	10.0	Small	Good	Good
L Cathode —pulsed					

CATHODE CONSTRUCTION

In Fig. 1 we show cross-sectional views of two types of planar L cathodes. The essential parts are the molyb-

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[1] H. J. Lemmens, M. J. Jansen, and R. Loosjes, "A new thermionic cathode for heavy loads," *Philips Tech. Rev.*, vol. 11, pp. 341–350; June, 1950.

lenum body *A*, the porous tungsten plug *B*, the barium-arbonate emission material *P*, and the heater *F*. The tructure on the left-hand side is a mechanically fitted lesign, in which the molybdenum body *A* is peened lightly over the porous tungsten plug to hold it in lace and form a tight joint. In the structure on the ight-hand side, the porous tungsten plug is welded irmly to the molybdenum body. It has been found that he welded construction has been in general more satisactory than the mechanically fitted construction.

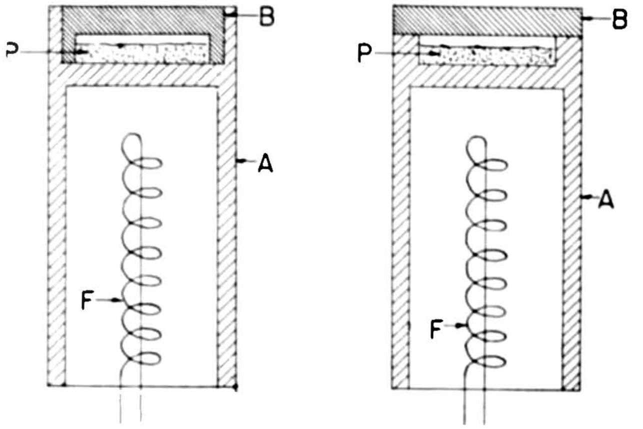

Fig. 1—L cathodes, planar types.

Fig. 2 shows cross-sectional views of two different types of cylindrical L cathodes commonly used on magnetrons, the cathode indicated on the left being of the indirectly heated type, while the one on the right is of the directly heated construction. For cathodes having small diameters, in the order of a millimeter, the cathode on the right-hand side is sometimes preferable. The indirect heater design is recommended for use where the cathode diameter is greater than 2 millimeters.

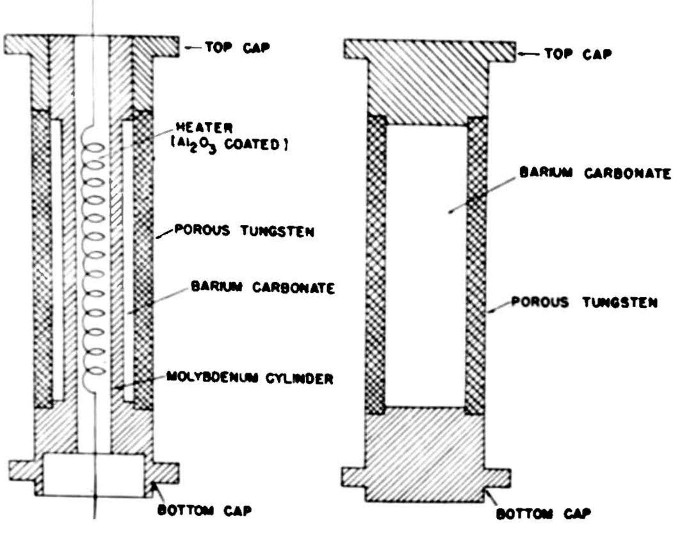

Fig. 2—L cathodes, cylindrical types.

The porous tungsten part for the types of cathodes shown is made by compressing tungsten powder and then sintering it at a high temperature.

ACTIVATION

In Table II we show a typical activation schedule. Steps 1 and 2 are more or less standard procedures for most evacuation schedules. In step 3, the barium carbonate is reduced to barium oxide. Step 4 is a preliminary step prior to the anode heating which is accomplished in step 5. Approximately 5 minutes are required to outgas the anode. Step 6 is the actual activation step in which the barium oxide is partially reduced to barium, which diffuses through the porous plug, reaching the outer surface in about 15 minutes to form a uniform emitting surface. An emission of 250 ma corresponds to 3.0 amp per cm^2 for a 3-mm diameter planar cathode.

TABLE II

1—Seal diode to vacuum system and check for leaks.
2—When vacuum is better than 1×10^{-4} mm of Hg, bake diode at 400 to 450°C for approximately 30 minutes.
3—Remove oven and glow heater, raising cathode temperature gradually to 1,130°C and maintaining a vacuum better than 1.0×10^{-4} mm of Hg.
4—Glow cathode at 1,270°C[2] brightness for one minute. Vacuum is better than 10^{-6} mm of Hg at end of this step.
5—Heat anode by radio-frequency induction to maximum recommended value (1,200°C brightness for zirconium-coated molybdenum) until vacuum is better than 1.0×10^{-6} mm of Hg.
6—Activate cathode at 1,270°C brightness, apply anode voltage adjusting anode voltage to 200 volts dc. Stop activation when emission current reaches 250 ma. Vacuum is better than 1×10^{-6} mm of Hg.
7—Seal from vacuum system.

EMISSION CHARACTERISTICS

The factor of primary interest when comparing different cathodes is the temperature dependency of the emission. Fig. 3 shows how the L cathode compares with other conventional cathodes.

Here the saturation emission measured under pulsed conditions in amperes per square centimeter is plotted against the true temperature in degrees C. The vertical dotted line indicates approximately the maximum temperature at which the cathode can be used to give a life in the order of some hundreds of hours. Under dc conditions, the oxide-coated cathode cannot be used continuously for more than one hundredth part of the saturation current at 900 degrees C since the emitting area is damaged if this value is exceeded. The other types of cathodes can operate continuously with an emission close to the saturation value.

The termination point of the curves is at the maximum value of temperature at which the respective emitters can be operated. Operation at temperatures beyond these points usually results in destruction of the cathode. It is noted that for an oxide-coated cathode 120 amp per cm^2 can be reached under pulsed conditions, while for an L cathode about 300 amp per cm^2 can be attained. This value is not limited to pulsed conditions, but can be realized under cw conditions. How-

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[2] All temperatures listed, with the exception of the oven temperature, are brightness temperatures measured on the molybdenum part.

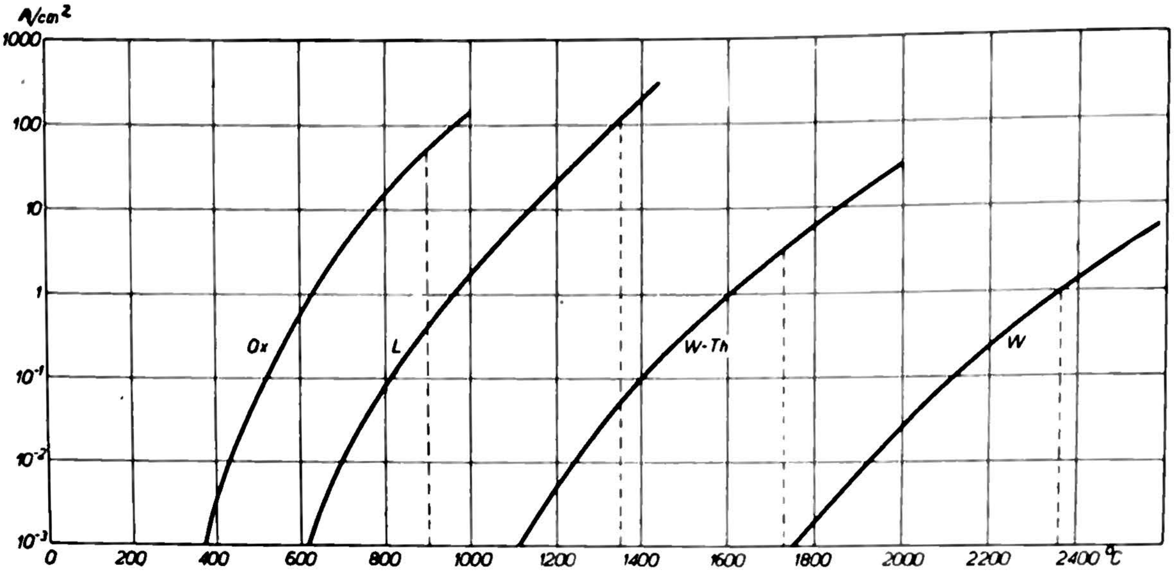

Fig. 3—Saturation emission J_s (amp per cm²) as a function of true temperature (degrees C). This curve has been taken from an article, entitled "A new thermionic cathode for heavy loads." See footnote 1.

ever, operating an L cathode under these conditions imposes other restrictions, namely, the problem of dissipating the anode power. In one test, a planar cathode having 6 mm² of surface area was assembled into a diode structure having a water-cooled anode spaced 0.5 mm from the cathode. The emission obtained was 40 amp per cm² at an anode voltage of 400 volts. Anode dissipation was in the order of 1 kw. The power input into the cathode had to be increased to maintain it at a temperature of 1,300 degrees C brightness since electron cooling at this current density is appreciable.

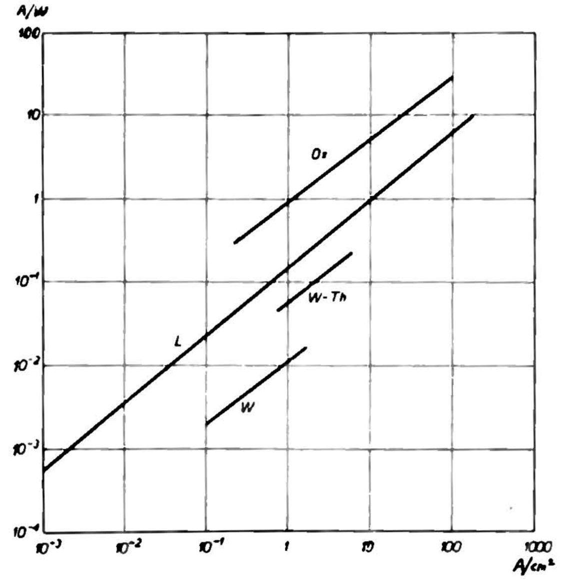

Fig. 4—Theoretical thermal efficiency (amp per watt) as a function of saturation emission (amp per cm²). (Taken from article entitled, "A new thermionic cathode for heavy loads.") See footnote 1.

In Fig. 4 we plot the theoretical thermal efficiency (in amp per watt heating power) as a function of the saturation emission expressed in amp per square cm. Here we note that the theoretical efficiency of the L cathode is greater than that of the tungsten and thoriated tungsten cathodes, but is less than that of the oxide-coated cathode. This is to be expected since the temperature of the L cathode is higher than that of the oxide-coated cathode with equal saturation emission. We appreciate that the oxide-coated cathode is the most efficient, and is highly desirable in applications where the current densities are less than 0.25 amp per cm²; but where higher densities and life are desired, we must scrutinize the thermal efficiency more closely before drawing any conclusions. If we consider an L cathode operating at a dc emission of 40 amp per cm² and multiply this value by 1.8 volts, which is in the nominal work function for the L cathode, the electrons emitted carry 72 watts per cm² out of the cathode. The heating power must therefore be increased by a like amount in order to keep the cathode surface at the temperature required for the emission. Without emission, a power of 20 watts per cm² would be adequate for this temperature.

As for the surface of the L cathode, it displays a smooth metallic emitting surface. The structure possesses great mechanical strength, and is not easily damaged in assembly. There are no particles to peel off under the influence of electrostatic attraction forces, as is the case for oxide-coated cathodes. The surface of the cathode can be turned on a lathe or molded, and it can be machined perfectly flat to exact dimensions within tolerances of a few microns. For disk-seal tubes, where cathode to grid distances are small (tens of microns) in order to shorten the transit times of the electrons, this feature offers excellent construction possibilities, even better than the finest grained oxide-coated cathodes which must be handled with care to prevent injury to the surface. For L cathodes, the surfaces can be made very small because of the high-emission density, thus making possible smaller interelectrode capacitances. The higher density emission cathode requires a high-control grid voltage in the case of grounded grid tubes, which shortens the transit time of the electrons and thus reduces the transit-time damping effect. The L cathode has no cross resistance of any consequence, in contrast to the emitting layer of the oxide-coated cathode.

Some of the inherent weaknesses of the oxide-coated cathodes are also prevalent to some extent in L cathodes, for instance, barium evaporation and susceptibility to poisoning by oxygen or oxygen compounds.

Under exposure to high-velocity gas ions or sparking, the emission of an L cathode recovers within approximately 250 milliseconds to its initial value because of a replenishment of barium to the emitting surface, while the oxide-coated cathode is permanently destroyed.

The most important feature of the L cathode is its life. Unlike the oxide-coated cathode, the life of which depends upon the emission current drawn as well as on the temperature at which it is operated, the life of an L cathode depends only upon the temperature at which it is operated and the quantity of barium oxide contained behind the porous tungsten wall. For a given planar-type cathode 3 mm in diameter, having a 7 mm^2 emitting area operating at 1,050 degrees C brightness, the amount of barium evaporation is 0.1 mg in 1,000 hours. Therefore, 1 mg of barium oxide should yield 10,000 hours of life at this temperature. A number of these diodes have run longer than 5,000 hours, drawing an emission current of 2.0 amp per cm^2 dc. Later we will discuss the methods of measuring the barium evaporation, as well as the life obtained to date, on some typical tubes.

Regarding the emission mechanism of the L cathode, let us consider the reaction which takes place. First, the barium carbonate pellet in the enclosed cavity is heated to 1,130 degrees C brightness until the carbonates are reduced to their corresponding oxides, the carbon dioxide being pumped out. Next, the cathode is heated to 1,270 degrees C brightness, and the barium oxide is partly reduced to barium. Thus barium vapor will collect in the closed chamber under a certain small equilibrium pressure. The barium vapor passes through the pores of the tungsten, and forms in those pores as well as on the surface a monatomic layer on the tungsten, bound to it by oxygen present on the surface. The formation of this layer results in a considerable reduction in the work function of the tungsten, from 4.5 to 1.8 volts. Thoriated tungsten cathodes have a work function of 2.75 volts. In Table III we illustrate some of the values of work functions and A values determined.

In Table III we note that the range of work function of the L cathode is between 1.6 and 2.0 volts. Experiments run whereby the barium-carbonate pellet was omitted in the L-cathode structure, and the external surface was coated by evaporating a monatomic layer of barium (using Ba azide). This resulted in a work function of 1.66 volts as shown. However, when the normal BaSr carbonates were sprayed on the outside surface (omitting the pellet), a work function of 1.1 was obtained. This is noticeably different from the L cathode. Hence we feel that barium plays the same role in the L cathode as does thorium in the thoriated tungsten cathode, and therefore, perhaps, should be called a "bariated" tungsten cathode.

TABLE III

Type Cathode	*Work Function (Electron Volts)*		*A (A/cm^2/deg^2)*	
Tungsten	4.44 to 4.63		22 to 210	
Thoriated tungsten	2.6	2.9	3	15
Oxide cathode	1.0	1.5	0.01	5
L Cathode	1.6	2.0	1	15
Barium evaporated on porous tungsten plug	1.66		—	
Thick BaO layer on porous tungsten plug	1.1		—	

BARIUM EVAPORATION

Before discussing the applications of the L cathode in various types of tubes, we will consider the methods used to investigate the rate of evaporation of barium.

Two methods were employed: The first method involved measuring a fixed quantity of barium carbonate which was inserted into the dispenser of a 3-mm diameter planar cathode prior to activation and life testing. At the end of life, zero emission resulted, and only a trace of barium oxide was present in the dispenser as well as in the porous tungsten plug. Fig. 5 indicates the results obtained for different values of temperatures. The log of rate of barium evaporation was plotted against the reciprocal of the absolute temperature.

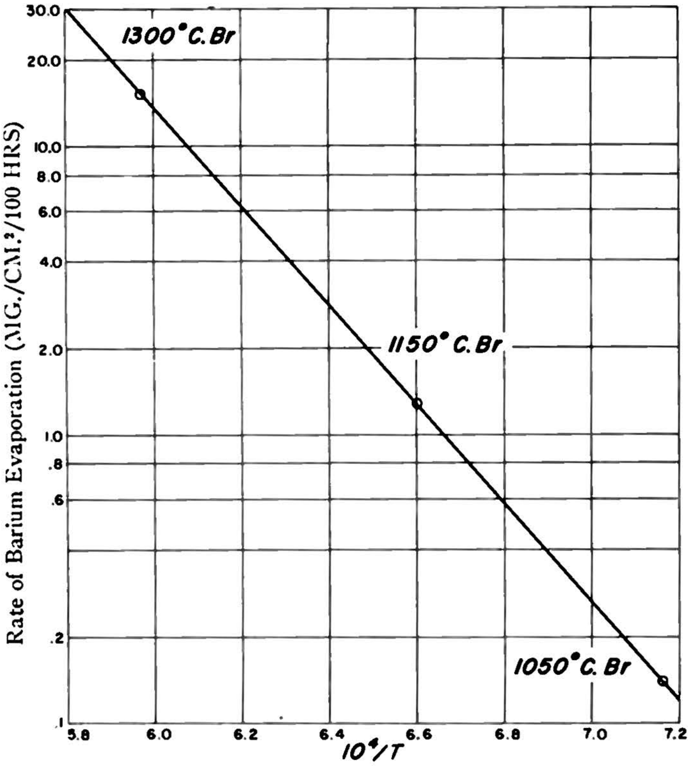

Fig. 5—Barium evaporation curve.

These data are for a particular cathode. It is possible to fabricate cathodes having a very much lower rate of barium evaporation.

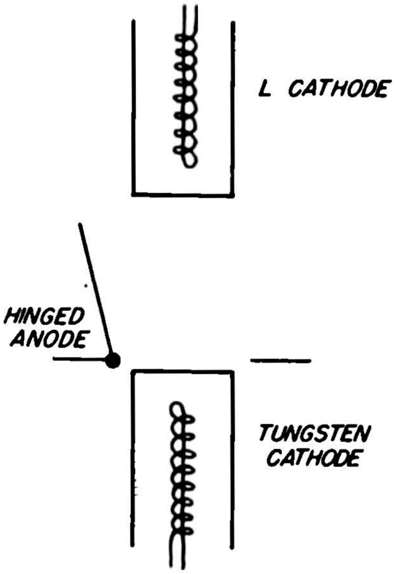

Fig. 6—Schematic of test diode to study barium evaporation.

In the second method, the rate of evaporation of barium was measured by using a simple diode as shown in Fig. 6. Here we show a simplified version of the diode construction. The tungsten cathode shown consists of a highly polished 100-per cent density, 3-mm diameter tungsten cathode, welded to a molybdenum cylinder and heated indirectly by the filament shown. The hinged anode is spaced approximately 0.025 inch from the tungsten cathode. The L cathode is of the standard 3-mm diameter type, and is mounted approximately 0.750 inch from the tungsten cathode. The walls of the glass envelope are approximately the same distance away. No getter is used in this tube, in order to facilitate taking brightness temperature of both cathodes. This diode is processed in the usual manner. The anode is rf bombarded, and both cathodes are heated to 1,300 degrees C brightness until the vacuum is better than 1.0×10^{-7} mm of Hg before sealing off.

After tip off, in order to remove all traces of barium, the tungsten cathode is glowed at 1,300 degrees C with the hinged anode closed and emission voltage applied until the anode current reads zero emission. At this point, the tungsten-cathode heater is turned off, and the hinged anode is opened by tilting the tube. The L-cathode anode is then glowed at any desired temperature, usually between 1,000 degrees C and 1,300 degrees C brightness. At periodic times, the L-cathode heater is turned off, the hinged anode is closed, and the emission is measured from the tungsten cathode operated at 800 degrees brightness, at which temperature barium sticks well to the tungsten surface. When the emission current from the tungsten-cathode stabilizes after successive exposures to the L cathode, a Richardson plot is taken from which the work function is computed. Successive exposures to the L cathode are continued to insure that stable work function has been reached. The rate of barium evaporation by this method appears to be in close agreement with the barium-depletion method described above.

LIFE

As mentioned previously, the most important contribution of the L cathode, aside from the fact that it can be operated at high-current density, is its lifetime, which is a function of the temperature of operation as well as the amount of barium oxide available from the reservoir. Unlike the oxide-coated cathode, its life does not depend upon the value of the emission current drawn from the cathode. The life can be computed from Fig. 5. For a given 3-mm diameter planar-type cathode having 2 mg of barium oxide in the dispenser, a life of approximately 200 hours is obtained at a cathode temperature of 1,270 degrees C brightness. Operation of the same cathode at 1,050 degrees C brightness results in a life of 20,000 hours, drawing an emission current of 2.0 amp per cm². Life test failures indicate that only a trace of barium remains in the dispenser as well as in the porous tungsten part.

One of the main causes of failure of L cathodes at true temperatures from 1,250 to 1,350 degrees C is the heater. Heaters coated with aluminum oxide apparently have satisfactory life if operated at true temperatures less than 1,200 degrees C.

In Table IV we list a number of experimental tubes in which the L cathode was used as an emitting source.

TABLE IV
EXPERIMENTAL L CATHODE TUBES

	Life (hours)
Cathode-ray 25-kv TV projection	1,000
Klystron two-resonator 2.8 to 3.5 cm 100 watts	5,000
Magnetron, 3 cm, pulsed 1,065-kw 45 per cent eff.	1,000
Rectifier, air filled 3.0 amp per cm²	3,000
Rectifier, H_2 filled, no emission	
Triode, disk seal 10 cm	1,600

The first tube listed is a cathode-ray tube of the 3NP4 type. A 3-mm diameter cathode with tantalum heat shields was used. It is important in the cathode design that the cathode is not assembled in intimate contact with ceramic spacers which tend to reduce to metals and poison the cathode surface.

The two-resonator klystron indicated also uses the 3-mm diameter cathode with tantalum heat shields and focussing assembly. Its construction is of the gridless type, having a beam diameter of approximately 0.086 inch. The life indicated has been obtained on a number of such tubes in which oxide-coated cathodes failed after 10 hours. No appreciable loss of Q or power output was experienced through life. Analysis of completely life-tested tubes indicates that the bulk of the evaporated barium is deposited on the side walls of the drift space, and very little barium is present inside the cavities.

The life of magnetrons using L cathodes is equally satisfactory. The magnetron listed is of the "rising-sun" type. Several cw magnetrons are now being constructed for noise-measurement investigations.

Regarding the rectifiers indicated, it is interesting to note that the hydrogen-filled rectifier indicated no emission, which is perhaps attributable to hydride formation.

CONCLUSIONS

In conclusion, let us summarize the essential features and properties of the L cathode. It consists essentially of barium oxide contained behind a wall of porous tungsten. During the operation of the cathode, the barium oxide is reduced gradually, and free barium resulting from this reduction escapes through the pores and forms on the surface a monatomic layer of barium bound to the surface of the tungsten by oxygen. Hence the work function of the tungsten is reduced from 4.5 to 1.8 volts.

The essential advantages of the L cathode are its capacity to produce high-thermionic emission, combined with long life. The life of an L cathode is dependent entirely upon the temperature of operation and the amount of barium oxide available in the dispenser. It is particularly suited for application in microwave tubes since it can be machined to exact tolerances.

ACKNOWLEDGMENT

Some of the discussion has been taken from the paper of H. J. Lemmens, M. J. Jansen, and R. Loosjes, *Philips Tech. Rev.*, vol. 11, pp. 341–350; June 1950, as well as from private communications with R. Loosjes.

The author wishes to express his gratitude to O. S. Duffendack, F. K. du Pré, and E. S. Rittner, for their interest and their many valuable suggestions.

The Theory of Amplitude-Modulation Rejection in the Ratio Detector

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***Summary*—The procedure for a complete mathematical analysis of the AM-rejecting properties of the ratio detector is presented. The operation with 100-per cent efficient diodes is first treated, and it is shown that in this case compensating resistors which reduce the effective efficiency of the diodes must be used to obtain optimum AM rejection. The operation with practical diodes is then treated and design charts for optimum AM rejection are presented. From the theory, the effect of variations in ratio-detector transformer parameters upon the AM-rejection properties is predicted. Unbalanced effects and the manner in which they can be made to cancel each other mutually are briefly described. It is pointed out that the degree of apparent limiting action within the ratio-detector circuit is incidental and unrelated to its AM-rejection properties, and thus represents an inadequate design basis for the ratio detector.**

I. INTRODUCTION

IN ORDER to obtain the full benefits of FM reception, an FM receiver should include an FM-detector system which is insensitive to amplitude modulation. A few years ago a new FM detector, called the "ratio detector," which did not require the use of a limiter, was introduced in receivers being marketed. Since then this detector has been rather widely use in FM receivers and in the sound ends of television receivers. However, in spite of wide usage, the design of the ratio detector is still almost entirely empirical. Several papers have been presented giving a general story on the operating characteristics of this device, but an accurate mathematical analysis has not been presented and the AM-rejection properties have not been adequately explained. The purpose of this paper is to outline a procedure for a complete mathematical analysis of the AM-rejection properties of the ratio detector, giving the results of the complete analysis in the form of graphs to be used for designing ratio-detector circuits. Since a description of the general operating characteristics has been given in the literature,[1] it will not be repeated here.

The complete mathematical analysis of the AM-rejection properties of the ratio detector is lengthy and involved. Presentation of all steps is therefore beyond the scope of this treatment.[2] Instead, the procedure followed will be outlined and the essential background material presented. The complete analysis produces results which are in agreement with experiment. These results will be presented.

II. THE RATIO DETECTOR AND ITS EQUIVALENT CIRCUIT

The mathematical analysis of the ratio detector is simplified through the use of an equivalent circuit. The development of this equivalent circuit from a ratio detector, using either a phase-variation discriminator transformer or a side-tuned transformer, is shown in Fig. 1. The rf circuit components to the left of terminals

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[*] Decimal classification: R361.2×R148.3. Original manuscript received by the Institute, February 16, 1950; revised manuscript received, June 18, 1951.

[†] Hazeltine Corp., Little Neck, L. I., N. Y.

[1] B. D. Loughlin, "Performance characteristics of FM detector systems," *Tele-Tech*, vol. 7, p. 33; January, 1948.

[2] The complete mathematical analysis is given in the Hazeltine Electronics Report #7096.