Current Rating and Life of Cold-Cathode Tubes

G. H. ROCKWOOD
MEMBER AIEE

Introduction

A COLD cathode tube is a gas discharge device capable of serving as a relay, a rectifier, or a voltage regulator.[1,2] It depends for its action upon the properties of gas discharges. The salient property employed is the fact that there is a difference between the breakdown voltage, or voltage necessary to initiate a discharge, and the sustaining voltage, or voltage drop across the tube when conducting. The principles involved are not new but a practical device capable of operating on voltages of 150 volts or less has awaited the relatively recent development of suitable cathode coating materials. The cathode surface employed at present consists of a coating of barium and strontium oxides applied to a nickel base. These oxides are partially broken down to barium and strontium metal during exhaust. During the operation of the tube the barium is continually removed from the cathode by sputtering and is replaced by further reduction of the oxide reservoir. The life of the tube is limited, therefore, by the amount of material present and by the rate of sputtering.

Because the cold cathode tube requires no cathode heating power it is well adapted to those applications in which the service is intermittent. The absence of a hot cathode implies no deterioration during idle periods and the ability of the tube to start instantly upon the application of an input signal. These properties have opened a wide field of use to the cold cathode tube and it is felt that this field may be widened if the tubes are so rated as to take cognizance of the fact that their life is determined by sputtering and the consequent exhaustion of the reservoir of cathode material. Other gas tubes, such as vapor rectifiers and thyratons, have been rated in terms of peak and average current. These ratings have been based on anode power dissipation and electron emission capability of the cathode surface. In the case of the cold cathode tubes it is desirable to have the rating bear a relationship to the rate of sputtering. For a tube of given manufacture, the rate of sputtering is determined solely by the current drawn. The general form of the life rating should be, therefore, a tabular relationship between the average life to be expected and the current. Several values of current and life are needed since the rate of sputtering is not proportional to the current.

If a cold cathode tube is operated until it fails in service certain changes may be observed visually. These are: first, a dark band on the tube walls in the vicinity of the cathode and, second, a change in color and surface appearance of the cathode. These observations may be accounted for by assuming that the cathode material is lost by either evaporation or sputtering. To test the idea of loss of material due to evaporation thermocouple measurements of the cathode were made. These measurements indicate that, in general, the cathode temperature is less than 250 C and invariably less than 375 C. These temperatures are so low as to make the theory of loss of material by evaporation untenable. For example, the cathode temperature at a current of 35 milliamperes was found to be 210 C and the average life 100 hours. Rudberg and Lumpert[5] have measured the vapor pressure of barium at low temperatures and give a formula by means of which their data may be extrapolated. From this knowledge of the vapor pressure of barium at 210 C and the total amount of barium present on the cathode the life may be calculated and it is found to be 45,000 hours compared to the 100 hours actually observed.

Microchemical examination of the tubes indicates that new tubes have considerable metallic barium on the surface of the cathode together with a much larger amount of barium in combination. Similar tests on tubes which have reached the end of their life indicate less metallic barium on the cathode and almost no barium in combination on the electrodes but the total barium which was present when the tube was made is to be found on other parts of the tube, notably the walls.

These facts lead to the conclusion that as the tube is operated barium is continually lost from the cathode surface by sputtering and is continually replaced from the reservoir of barium oxide provided in the cathode coating. When this reservoir is exhausted the tube reaches the end of its life.

Theory of Cathode Sputtering

Most of the literature on cathode sputtering relates to a discharge at relatively low pressures and with high voltage drops across the tube. The only comprehensive survey of sputtering in low voltage tubes is to be found in a paper by C. H. Townes.[3] A review of the conclusions reached by Townes is given below.

Townes divides the rate of sputtering into three factors: (1) the number of ions of a given energy striking the cathode, (2) the amount of material released by each ion, and (3) the fraction of material released from the cathode which diffuses away and ultimately reaches other surfaces in the tube.

There is good evidence that sputtering is due to ionic bombardment of the cathode and that the material sputtered leaves the cathode in all directions and in an uncharged atomic stage. In the low voltage cold cathode tube the cathode dark space, across which appears the cathode fall of potential has a thickness of several electron mean free paths. The mean free path for a positive ion being smaller than that for an electron, it is evident that very few, if any, positive ions reach the cathode with an energy corresponding to that of the cathode fall. The average energy of positive ions impinging on the cathode is found to be a little less than one electron volt. Not only the average energy is necessary but also the probability that an ion has any of the various possible energies. Appreciable variations in the total energy come principally from the variation in the energy acquired at the last free path of the ion. This follows from the fact that collisions between ions and gas atoms are collisions between particles of substantially equal mass so that on the average, an ion will lose half of its energy at each collision. On the average, therefore, the energy acquired by an ion in its last free path is double that which it had at the beginning of this last free path. The final expression for the distribution in energy of the positive ions striking the cathode is an exponential expression of the same form as that describing the distribution of molecular free paths in a gas. This is to

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G. H. Rockwood is with the Bell Telephone Laboratories, Inc., New York, N. Y.

1. For all numbered references, see list at end of paper.

be expected since, as pointed out above, the principal variation in the energy comes from that acquired in the last free path, or in other words depends upon the length of the last free path.

Of the mechanisms suggested for the release of material from the cathode under positive ion bombardment the one most successful in explaining the experimental results is the theory of local heating and resultant evaporation of von Hippel.[4] According to this theory the positive ion delivers its kinetic energy to a small number of atoms on the surface which are temporarily given large random velocities and evaporate from the surface just as they would evaporate if the entire cathode were heated so that they had the same thermal energy. The local hot spot of course, cools very rapidly by sharing its energy with the surrounding atoms. Townes has developed an expression for the number of atoms removed from the cathode by each ion impinging with a given energy. For a cathode material such that an atom must have an energy of four electron volts to escape from the surface his expression leads to the following:

Atoms Removed Per Ion Striking Cathode	Energy of Impinging Ions
2×10^{-8}	4 e.v.
0.2	6 e.v.
2	8 e.v.

This demonstrates the rapid variation in the number of atoms removed per impinging ion as the energy of the impinging ions is increased. The expression for the total number of atoms released from the cathode considering the distribution in energy of the positive ions reaching it is complicated and will not be given here.

Since the mean free path of the sputtered particles is much smaller than the distance between the cathode and surrounding surfaces a large fraction of the atoms which leave the cathode will diffuse back to the cathode surface so that they do not represent a net loss of cathode material. Townes shows that for a fixed rate of evaporation of atoms at the cathode the actual rate of loss of material from the cathode is inversely proportional to the gas pressure and depends as well on the distance to the nearest surfaces where deposition may take place. A large number of the evaporated atoms return to the cathode surface. The exact number lost will, of course, depend upon the tube geometry.

The complete expression for the sputtering rate is given by Townes as:

$$I = AF\frac{J}{p}e^{-\left[\frac{V_0}{c}\left(\frac{p^2}{Vi}\right)^{2/5}\right]} \tag{1}$$

where

I is equal to the mass per second of sputtered material

p is the gas pressure in millimeters of mercury

V is the cathode fall in volts

i is the current density in amperes per square centimeter

V_0 is the energy in electron volts required to remove one atom from the cathode surface

c is a constant characteristic of the gas. For argon $c=20$, for neon $c=33$

J is equal to the total current

F is a function determined by the geometry of cathode and collecting surface. For plain parallel surfaces $F=1/d$ where d is the distance between the surfaces

A is another constant evaluated in terms of the properties of the cathode material in the gas

The constants in this equation may be approximately evaluated on theoretical grounds or they may be determined by experiment.

Experimental Results

A series of tubes have been operated at various currents to determine experimentally the relationship between current drawn and life. The cathodes of these tubes are coated to a nominal thickness of one-half milligram per square centimeter. This is an extremely thin coating and it is difficult to reproduce such coatings exactly from tube to tube. Considerable scattering in the test results must be expected therefore. The points on the curve of figure 1 each represent the average life of three tubes operated under the current conditions noted. The curve represents equation 1 with the constants so selected that it represents the best fit for the data. The agreement between the curve and the experimental data is seen to be quite satisfactory considering the scattering that must be expected in experiments of this type and suggests that the assumption at the outset that the life of the tubes was determined by the loss of cathode material due to sputtering is correct. This being so it seems reasonable to rate the tubes in such a manner as to reflect this fact.

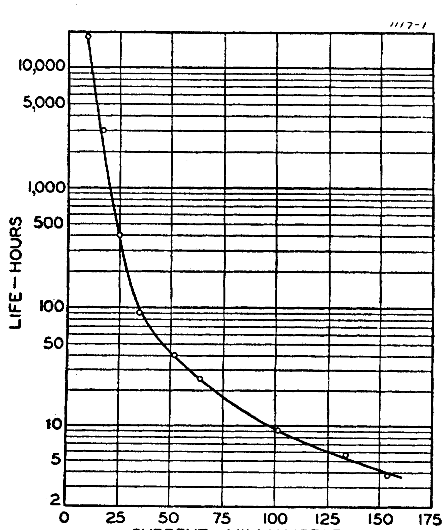

Figure 1. Life of the Western Electric 313C cold-cathode tube as a function of current

The data presented in figure 1 relate to a Western Electric 313C vacuum tube and form the basis for the current ratings for this tube. The ratings employed are those currents which will give a life of 100, 1,000, and 10,000 hours. Because of the large scattering due to variations in coating thickness and gas pressure in individual tubes it is not expected that the life of a single tube can be predicted with an accuracy better than $\pm 50\%$. In dealing with large numbers of tubes, however, the average life is predicted with a considerably better accuracy. It is practical, for instance, to use this curve in calculating the number of tube replacements required for a circuit which operates under given conditions.

Application of Current Ratings

Since the life of a cold cathode tube of given manufacture depends solely upon the current drawn a knowledge of the relationship between life and current drain is of vital importance to the circuit designer. In the use of cold cathode tubes it often happens that the duty cycle is so light that the life of the tube may be many times the life of the equipment in which it is used even though the tube, if operated continuously, might last but a few hours. If the circuit designer is furnished with the relationship between life and current drain and knows the duty cycle imposed on the tube he is in a position to determine the average life he may expect from the tube. With this knowledge it is often possible to apply small, inexpensive cold cathode tubes to circuits requiring considerable amounts of current for brief and infrequent intervals rather than to resort to larger tubes requiring hot cathodes and capable of supplying the current continuously. Likewise, it makes it possible for the designer to reach a reasonable compromise in decreasing the cost of associated equipment at the expense of increasing the current drain through the tube and therefore shortening the tube life.

If the current wave form through the tube is irregular the life may still be pre-

Dielectric Strength of Oil for High-Voltage Testing of Oil Circuit Breakers

H. J. LINGAL
MEMBER AIEE

W. F. SKEATS
MEMBER AIEE

H. D. BRALEY
ASSOCIATE AIEE

THE purpose of this paper is to report on work undertaken in response to a request, made to the Institute, to determine the minimum dielectric strength of oil for high potential testing of oil circuit breakers.

Many tests were made with 60-cycle and impulse voltages. The tests were made with a rod to plane gap, cone to disc gap, and on oil circuit breakers of commercial types and sizes. The results of these tests have been collected, analyzed, and are included in tabular form in the paper.

The impulse strength of oil circuit breakers was found to be practically unaffected by the 60-cycle breakdown strength of the oil within the range of 16 to 30 kv, as measured in a standard test cup.

The 60-cycle dielectric strength of oil circuit breakers is shown not to be changed in direct proportion to the differences in the dielectric strength of oil as measured in a test cup with 60-cycle voltage.

The effect of low dielectric strength oil on voltage breakdown is discussed and conclusions are drawn which show that it is desirable to test all oil circuit breakers with oil having dielectric strength of 22 kv or higher.

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H. J. LINGAL is with Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., W. F. SKEATS with General Electric Company, Philadelphia, Pa., and H. D. BRALEY with Consolidated Edison Company, New York, N. Y.

The authors of this paper are the members of a working group of the circuit breaker switch and fuse subcommittee of the AIEE protective devices committee, who were appointed to investigate and recommend the proper dielectric strength of oil for high-potential testing of circuit breakers.

1. For all numbered references, see list at end of paper.

General

The general picture of oil breakdown for some years has involved the lining up of impurities over a period of time ranging from a small fraction of a second to several minutes, with breakdown taking place over the path so formed. From this standpoint it is to be anticipated that long gaps will be relatively less affected by the impurities in the oil than short gaps, and that breakdowns under impulse conditions, where time is not available for lining up of impurities would be less affected by impurities than breakdowns under a one minute test at operating frequency. This is supported by the fact that the impulse ratio of oil, as obtained by comparing Sorensen's[1] data on impulse tests with Miner's[2] data at 60 cycles is considerably greater than the impulse ratio for breakdowns over an air path. Hence, it would be expected that any equipment which will flash over in an air path in preference to an oil path at 60 cycles will have a good margin of safety for the oil under impulse conditions, and it is also to be expected that the dielectric strength of a completed assembly such as an oil circuit breaker would be much less affected by the presence of impurities, in the oil, particularly under impulse conditions, than would be

Table I. Rod-to-Plane Gap Impulse Tests
(See Figure 1)

Gap Spacing (Inches)	Oil	Highest Voltage Held Without Breakdown (Kv)	Lowest Voltage at Which Breakdown Occurred (Kv)
1	New	176	168
1	Old	165	166
2	New	200	186
2	Old	208	190

The tests were made with a $1^1/_2$–40 m.s. positive wave.

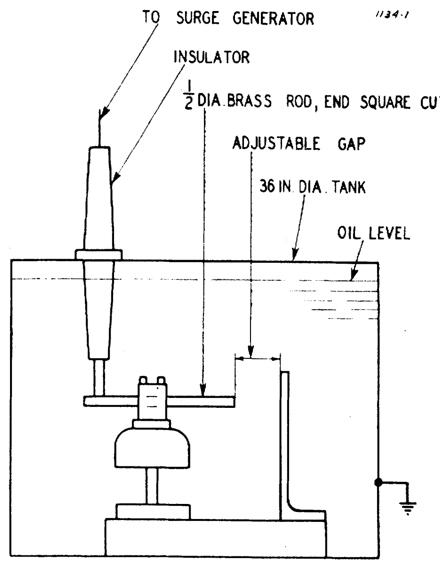

Figure 1. Rod-to-plane gap used in making tests shown in table I

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dicted by dividing the current wave into elements small enough so that the current in each element may be considered constant. Each of these currents may then be considered as lasting for a certain fraction of the cycle. For each of the current values obtained there is a life in hours which may be determined from figure 1. One then has a series of currents $i_1, i_2, \ldots i_n$ each lasting for a fraction $t_1, t_2, \ldots t_n$ of the entire cycle and a tube life corresponding to these currents of $l_1, l_2, \ldots l_n$. The fraction of life used up at each current per hour is, then t/l. The total fraction of life used up per hour is

$$\frac{t_1}{l_1}+\frac{t_2}{l_2}+\ldots\frac{t_n}{l_n}$$

and the socket life of the tube is

$$\text{socket life}=\frac{1}{\frac{t_1}{l_1}+\frac{t_2}{l_2}+\ldots\frac{t_n}{l_n}}$$

Conclusions

For tubes manufactured in any given manner the life will be determined solely by the current drawn. In view of the fact that the tubes do not deteriorate when they are not passing current it seems reasonable to operate them at very large currents if the duty cycle is sufficiently light. It is suggested, therefore, that the most useful type of rating for cold cathode tubes would be to state the current which will give a life of 100, 1,000, and 10,000 hours.

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