Heater-Cathode Insulation Performance

The insulation between the heater wire and the cathode of electronic tubes of the indirectly heated cathode type is required to conduct heat while maintaining high electrical resistance at operating temperatures. By means of cathode-ray oscillograms the effects of operating temperature, heat treatment, and impurities upon the electrical conduction of the commonly used insulating materials are shown in this paper.

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A PROBLEM in designing indirectly heated cathodes for electronic tubes is to provide a thermal connection between heater wire and cathode sleeve, operating in a vacuum at temperatures between 800 and 1,200 degrees centigrade, and at the same time to secure electrical insulation between heater and cathode circuits.

The high degree of mechanical stability required for the heater-cathode system combined with the smallness of space inside the cathode sleeve prohibits the use of a high vacuum for insulation. Furthermore, electron emission from the hot metal surfaces, although relatively small at the temperatures involved, would be increased greatly by diffusion of barium particles from the outside of the cathode. The necessity of maintaining a high vacuum within the tube prohibits the use of insulating materials that would develop an appreciable vapor pressure, or react chemically with the metals used for heater wire and cathode sleeve (tungsten and nickel).

INSULATOR MATERIALS

At the present time best results are obtained by using oxides of the lightest metals, such as lithium oxide (Li_2O), beryllium oxide (BeO), magnesium oxide (MgO), or aluminum oxide (Al_2O_3) as insulators. Standing in the upper series of the periodic system, these atoms have comparatively high ionization potentials. The oxygen atom is the foremost electronegative one and the light metals are strongly electropositive. Therefore, their chemical compounds form molecules which are not easily dissociated by electric stress or thermal movement. The molecular structure of these oxides is balanced electrically so well that at low temperatures practically no free electrons are moving between them to cause electric conductivity.

The excellent insulating properties of the oxides mentioned are available, however, only if the oxides are free from impurities. For instance, very small quantities of sulphur or phosphorus (see figure 6) as well as water and oxygen residuals can provide a large ionic conductivity. They change completely the electrical characteristic of the insulator, especially in the hot state. Therefore, the present objective is to develop simple and reliable processes to keep impurities within tolerable limits rather than to change the basic insulator material now in use.

At the time indirectly heated cathodes were introduced the cathode consisted of a metal tube in the center of which a straight tungsten heater wire was placed. The space between heater wire and cathode was filled completely by the insulator, a construction that resulted in a very large heat inertia—it took minutes to bring the cathode to operating temperature—and furthermore the insulation was poor (see figure 3). Great improvement came from the attempt to reduce the quantity of insulating material by placing it only where it actually was needed: around the heater wire. In modern tubes the heater element is wound in a double helical spiral or other form to neutralize its magnetic field. The tungsten wire forming it is sprayed with or dipped in a suspension in water of the insulating oxide, usually aluminum oxide, so that the surface of the wire is completely coated. The suspension of the oxide is ground carefully for 24 hours in a ball mill, and an organic binder is added to make it adhere to the heater wire. The binder evaporates during the firing process. The coated heater wire is dried in air and fired for about 5 minutes in a vacuum or dried hydrogen at about 1,700 degrees centigrade. After such heat treatment the insulation forms a rather solid and uniform layer about 0.5 millimeter thick around the heater wire. The heater so coated is inserted into a nickel sleeve, touching it at many points under light pressure. The nickel sleeve carries the emitting coating composed of about 75 per cent barium oxide (BaO) and 25 per cent strontium oxide (SrO) on its outer surface. Normally the cathode surface has an emitting temperature of 850 degrees centigrade and the temperature of the heater wire inside, as taken from resistance measurements, is about 1,000 degrees centigrade. In automobile radio receivers the tubes are operated at voltages between 5.5 and 8 volts. Corresponding surface and heater temperatures range from 800 to 950 degrees and from 950 to 1,200 degrees, respectively.

In most radio circuits the heater is a-c operated, and hum at the power supply frequency, caused by the reversing voltage drop along the heater wire (6.3 volts effective value in modern tubes) must not appear in the plate circuit. Some superheterodyne circuits apply the oscillator voltage in the cathode

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The experiments upon which this paper is based were made by the author in 1934 in the laboratories of the RCA Radiotron Company, Harrison, N. J.

circuit, so that radio frequency voltage exists between heater and cathode. Especially in such circuits the heater-cathode impedance must be large to avoid trouble.

The cathode is the most expensive part in radio tube manufacturing and, therefore, receives serious consideration. Although insulating materials such as beryllium oxide (BeO) and processes such as vacuum firing result in the highest quality, they are not generally used because of the greater expense. However, they will be dealt with in this paper as they help the physical understanding.

METHODS FOR INVESTIGATION OF THE ELECTRIC PROPERTIES OF HEATER-CATHODE INSULATION

This paper discusses tests for heater-cathode insulation, some of them made under exaggerated electric and thermal conditions, that give an insight into the physical behavior of the material rather than commercial tests for use under operating conditions.

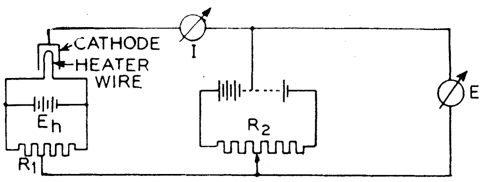


Fig. 1. Circuit for d-c measurements of heater-cathode insulation

Such knowledge of physical behavior is gained by applying external potentials up to several hundred volts between heater and cathode and measuring the resulting current flow as illustrated in figure 1. The resistances R_1 and R_2 are small compared to the resistance of the heater-cathode insulation. The cathode is connected to ground. To avoid effects of thermionic cathode emission into the surrounding space all free electrodes of the tubes tested were connected to the cathodes.

The heater voltage E_h causes the observed voltage-current characteristic to differ from the actual voltage-current characteristic of the insulating material. The actual voltage across the insulator is $E + E_h/2$ at one end and $E - E_h/2$ at the other end of the heater wire. Therefore, if E is applied between the center tap of the heater battery and the cathode, the observed total current is

$$I = \frac{1}{E_h}\int_{E-\frac{E_h}{2}}^{E+\frac{E_h}{2}} idE$$

Because of the geometrical configuration and material properties, the current i is not distributed linearly along the heater wire. Therefore any sharp break in the actual voltage-current characteristic of the material is somewhat displaced or smoothed in the observed characteristics. In the extreme case the observed characteristic may differ from the actual one by not more than E_h for any particular value of i.

Many of the voltage-current characteristics measured with continuous voltage show a definite time lag in reaching stable values, varying from fractions of a second to minutes. The longer times observed are similar to an "aging" effect and change the characteristic of the insulation in an irreproducible way. They are not considered at present, since such insulators are below the range of applicability in electronic tubes. The shorter time lags or hysteresis effects are, however, of special interest, and inasmuch as they cannot be examined properly by d-c measurements, a-c tests were made with a cathode-ray tube. The circuit is shown in figure 2.

Plates A and B of the cathode ray tube measure the voltage drop across the heater-cathode insulation. Plates C and D measure the voltage caused by the current through the insulation which flows through resistor R_3, a one megohm resistor. A 60 cycle alternating voltage of 180 volts peak was applied. A straight line on the oscillograph screen, crossing the voltage and current axes at 45 degrees and going through the center point, indicated an insulation of pure ohmic resistance of one megohm, without hysteresis and without counter electromotive force. Hysteresis effects appeared as a loop, counter-potentials caused off-center crossings, and non-linearities bent the straight line into a curve.

The data obtained from the tests described are not quantitative. They cannot be interpreted in terms of specific resistance over the voltage range of the experiments since they are obtained on conventional tube structures. In these structures neither the temperature distribution across the insulator nor the distance from heater to cathode is accurately definable. Experiments with systems less complicated than indirectly heated cathodes are necessary for completeness.

DISCUSSION OF EXPERIMENTAL RESULTS

The following test results show that perfection in heater-cathode insulation is not yet reached, but that it is possible to approach fair operating conditions. (A cathode is called "good" if at the highest operating temperature it has a resistance of about 10^7 ohms.) Figure 3 presents the voltage-current oscillogram of the old type cathode system, in which the whole space between heater wire and cathode was filled by the insulating material. The resistance of the insulating material (at rated temperature) remains constant at 2 megohms across the whole voltage range. In modern tubes, such as described hereinbefore, the insulation is in tight contact with the heater wire, but it touches the cathode only at

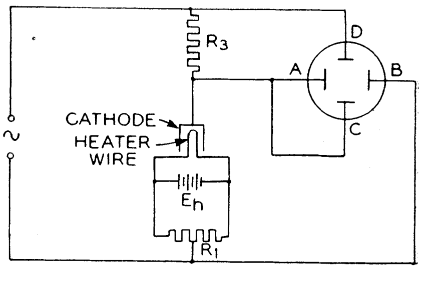


Fig. 2. Circuit for a-c measurements of heater-cathode insulation

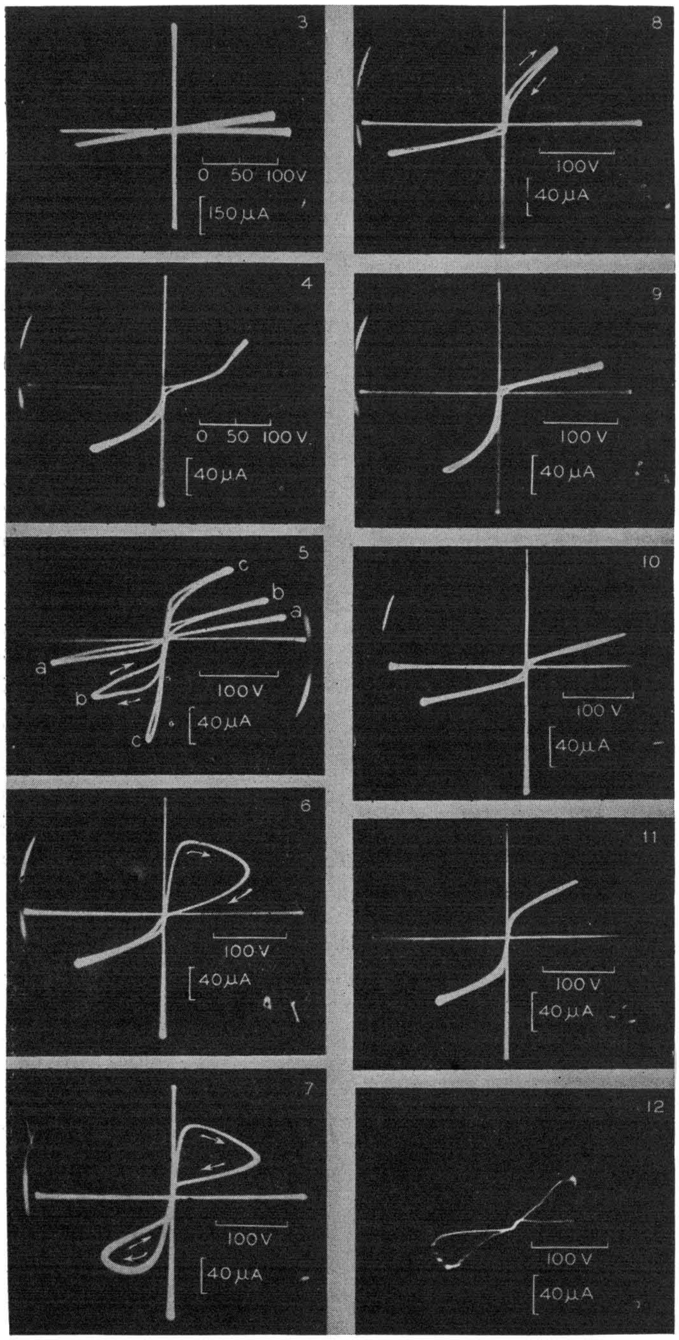
discrete points. These contact points are a source of nonlinearities in the voltage-current characteristic.

Figure 4 is the characteristic of such a modern heater-cathode system. Electron flow from cathode to heater wire (right side of all oscillograms) meets less resistance at higher voltage while in the opposite direction the resistance is low at low voltage and rises with increasing voltage. This oscillogram is typical of modern cathodes of fair quality. The nonlinearity on the left side is probably caused by limited conduction across the insulator while the high initial resistance on the right side is explained as high contact resistance, which breaks down at increasing field strength (at about 4,000 volts per centimeter). Slight loops in this oscillogram indicate that there is some small time delay between current and voltage, but the times observed are still small enough to suggest that current conduction is almost an electronic phenomenon.

A somewhat inferior cathode at 3 different temperatures gave the results presented in figure 5. At 700 degrees centigrade (curve *a*) the voltage-current line is almost linear, and only a small loop is visible on the left side; at 850 degrees centigrade (curve *b*) a larger loop is visible on the left side, and on both sides, especially on the right, it may be observed that the current does not follow the voltage rise substantially beyond a certain value. This phenomenon will be discussed later in more detail. At 950 degrees centigrade (curve *c*) the resistance is very low on the left side, but the current limiting or blocking phenomenon is still visible on the right side.

It appears that less severe heat treatment of the cathode presented in figure 5 is responsible for the increased ionic conductivity. This phenomenon was exaggerated in the 2 cathodes represented by the curves in figures 6 and 7. The cathode represented by the curve in figure 6 was fired at too low a temperature (1,600 degrees centigrade) and the hydrogen in which the firing took place was not dry. A large loop is visible on the right side of the oscillogram (heater wire positive). In this cathode insulator the amount of free oxygen was so large that the tungsten heater wire became oxidized after a few days of operation. The curve for the other cathode (figure 7) shows large loops on both sides. This cathode insulation consisted of carefully heat treated aluminum oxide (fired 5 minutes at 1,600 degrees in dried hydrogen), but it contained 0.5 per cent phosphorus pentoxide (P_2O_5) as a contamination. Similar tests with silicon dioxide (SiO_2) and tantalum pentoxide (Ta_2O_5) confirmed the fact that such contaminations are responsible for the observed electrolytic behavior.

Static measurements of such ionic or electrolytic insulations often show counterpotentials up to one volt. Such counterpotentials are able to produce currents of the order of 10^{-7} ampere for some seconds. If the cathode is cooled before the discharge takes



Figs. 3–12. Voltage-current oscillograms of heater-cathode insulation

Scales are in volts (*V*) and microamperes (μA)

Figure Number	Material of Insulation	Temperature of Cathode Surface, Degrees Centigrade	Heat Treatment, Temperatures in Degrees Centigrade
3	Magnesium oxide (MgO)	850	
4	Aluminum oxide (Al_2O_3)	850	Fired in vacuum at 1,650
5	Aluminum oxide (Al_2O_3)	700 (curve *a*)	
		850 (curve *b*)	
		950 (curve *c*)	Fired in vacuum at 1,600
6	Aluminum oxide (Al_2O_3)	900	Fired in wet hydrogen at 1,600
7	Aluminum oxide (Al_2O_3) and 0.5 per cent phosphorus pentoxide (P_2O_5)	950	Fired in dry hydrogen at 1,600
8	Aluminum oxide (Al_2O_3)	1,050	Fired in vacuum at 1,700
9	Aluminum oxide (Al_2O_3)	1,050	Fired in vacuum at 1,700
10	Aluminum oxide (Al_2O_3) and 1.0 per cent barium oxide (BaO)	1,050	Fired in dry hydrogen at 1,700
11	Aluminum oxide (Al_2O_3) and 1.0 per cent barium oxide (BaO)	1,125	Fired in dry hydrogen at 1,700
12	Beryllium oxide (BeO)	1,050	Fired in vacuum at 1,800

place, the current starts as soon as the cathode is heated again. This is a polarization effect similar to those observed in liquid electrolytes, and the transformation from the semiconductor state to the insulating state by cooling allows the storage of the charges. Cathodes of the ionic type operating with d-c bias between heater and cathode frequently suffer a sudden breakdown of the insulation, after a time, during which the resistance is almost constant or sometimes even increasing. This phenomenon is caused by ion migration. Although the leakage current is too small to form a metallic layer on the negative electrode, it is quite possible that metallic ions grow in the form of fine needles through the solid electrolyte until they bridge and short both electrodes.[1] The growth of such needles is speeded by the current concentration in front of the needle points.

The current limiting or blocking effect as mentioned in the discussion of figure 5 becomes more pronounced in cathodes which are treated at a higher temperature. The voltage-current oscillogram of such an insulator is given in figure 8. The temperature at which this oscillogram was taken was rather high in order to make the effect more pronounced in the picture. On the right side of the oscillogram, where the heater wire is positive, a large conductivity combined with a small loop is observed. With heater wire negative the current starts to rise quickly too, but at about 10 microamperes a sudden break in the curve occurs and the further rise of the current is small, linear, and reversible. The insulating action is polarized and looks somewhat like a rectification. A similar phenomenon, but occurring at the opposite polarity, is shown by figure 9.

Static measurements on cathode insulators which showed voltage-current characteristics similar to those presented in figures 8 and 9 confirmed the fact that the described break in the voltage-current characteristic is very sharp (the radius of curvature is about a tenth of a volt), and in some cases it was observed that the characteristic after the break was falling. The resistance of the insulator in the region of blocked current assumes high values, often ranging between 100 and 1,000 megohms. It sometimes surpasses the resistance of the same insulator at the same voltage in the cold state. Different thermal expansions of heater wire and cathode sleeve and change of contact pressure and area certainly are involved in this observation. At voltages higher than 200 volts (field strength of about 10,000 volts per centimeter) a sudden breakdown of the blocking action takes place at rated operating temperature, but previous conditions can be regenerated by aging at low voltage or opposite polarity.

Both cathodes presented in figures 8 and 9 consisted of pure aluminum oxide and were fired in vacuum at 1,700 degrees centigrade. Like those insulators in which an equally pronounced current blocking effect was observed they were treated at a higher temperature than those previously described cathodes which showed larger ionic conductivity. Experience seems to suggest that concentration of a certain number of ions on the border between semiconductor (hot insulator) and metallic electrode (heater wire or cathode sleeve) is responsible for the observed effect. Very intensive heat treatment (firing at more than 1,800 degrees centigrade) often destroys the blocking effect.

The oscillogram in figure 10 was taken on an insulator which was fired for 5 minutes in dried hydrogen at 1,700 degrees centigrade. The oscillogram was taken at high cathode temperature to bring the current up to easily observable values. A blocking effect on both sides of the oscillogram is visible. The insulation, except at very low voltages which can be avoided by using bias potentials, is excellent. Figure 11 presents the same insulation at a still higher temperature and shows increasing conductivity. In all these oscillograms a much more gradual break is observed for decreasing current than for increasing current.

Insulators which have had very severe heat treatment are sometimes unstable. Their voltage-current characteristic changes abruptly between a more or less proportional relation and a current limiting state. The frequency of occurrence of such changes is very irregular. It is influenced by mechanical knocks against the tube enclosure. In practice this phenomenon is called "microphonic" behavior, though it is different from the so-called microphonic insulation where chipping off of the insulating layer causes a variable galvanic contact between heater wire and cathode. Figure 12 is an example of an unstable cathode type. The time of exposure was 0.1 second (6 cycles). Two voltage-current characteristics and different sudden transitions from one into the other at different points are visible. The zero lines could not be photographed because of limitations of the shutter mechanism of the camera used.

Tubes having this microphonic behavior are very bad in radio circuits. It happens sometimes that a single microphonic tube raises the noise level of the apparatus beyond the amplitude of the audio frequency. It is believed that microphonic properties of the type described result from overheating during the firing process.

SUMMARY

Straight line voltage-current characteristics were observed only on old type cathode systems, where the whole space between heater and cathode sleeve was filled by the insulator. All modern cathodes, in which the insulation touches the cathode only at discrete points, show nonlinear voltage-current relations. If the insulating material is impure or if it is heat treated at too low a temperature, ionic conductivity and the occurrence of loops in the voltage-current oscillogram is observed. Cathodes with higher firing temperatures have reversible characteristics; cathodes fired at too high temperatures are unstable.

Under certain conditions a very pronounced current limiting or blocking effect is observed. It might be that an oxygen layer on the border between semiconductor and metallic conductor is responsible for this effect. Beyond this it is too early to ad-

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

vance theories. Observation of heater-cathode systems alone does not supply sufficient evidence for a complete description of the phenomenon. However, it may not be out of place to mention the cold "blocking layer" or copper oxide rectifier phenomenon,[2] whose similarity might be more than accidental. Further experiments, especially capacity and high frequency measurements, are necessary. Such investigations may lead to useful applications of heated semiconductor devices.

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Impulse Voltages Chopped on Front

Problems arising from testing with impulse voltages chopped on the rising fronts of the waves are discussed in this paper. A consideration of the generation and measurement of impulse voltages is presented briefly, and the problems are studied in a discussion of the test results. The subject is treated nonmathematically and the results analyzed in terms of physical interpretation.

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LABORATORY STUDIES of steep impulse voltages chopped on the front have been undertaken for the reason that such voltages can occur on transmission lines. Present knowledge indicates that this type of impulse appears as the result of direct strokes of lightning and on parts of the line near the point of incidence of the stroke. An important consideration of the general subject for future development will be securing more field data on the impulse voltages which appear on electric circuits as the result of lightning. In fact, it is only by a correlation of field and laboratory data that the relative value of impulse voltages chopped on the front can be established practically on a sound basis.

IMPULSE VOLTAGE GENERATION AND MEASUREMENT

The impulse voltage generator[1,2] can be represented for practical purposes by the simplified circuit of figure 1. In principle the impulse generator consists of capacitor units charged in parallel from a source of rectified alternating voltage and discharged in series by means of gaps to develop the required voltage. The wave form of the generated voltage appearing at the test load is fixed by the constants of the load and the generator, and may be controlled to a certain extent by the constants of the generator.

Representative constants for a high voltage generator when testing rod gaps, insulators, and bushings with the recommended A.I.E.E. $1^1/_2$x40 microsecond wave[4] are the following: $C_s = 8{,}000$ micromicrofarads, $L_{S1} = 60$ microhenrys, $R_s = 500$ ohms, $C_2 = 600$ micromicrofarads, and $R = 9{,}000$ ohms. In generators for medium and low voltages the value of C_s is larger and that of C_2 smaller; the other constants can be adjusted to give the recommended wave.[3]

In general, steep fronted waves cannot be obtained when large transformers are tested. Representative constants for a large power transformer are $C_T = 2{,}500$ micromicrofarads and $L_T = 0.12$ henry. Furthermore, since a lead is essential to connect the apparatus to be tested to the generator and a liberal test set-up is necessary in practical testing, the resulting lead inductance L_{S2} may approach in value the inductance L_{S1} of the generator. For these reasons fronts up to $2^1/_2$ microseconds are permissible with such transformer loads[5,6]. Experience during several years has well demonstrated the feasibility of testing practically all types of electrical apparatus with the nominal $1^1/_2$x40 microsecond wave. In such testing the impulse voltage generated is developed to the full crest value. In this method of testing, the impulse voltage can be controlled readily with full assurance by simple adjustment of the rectified alternating voltage which charges the capacitors of the generator.

When tests are made with impulse voltages chopped on the rising front, a rod gap or other suitable device is employed which chops the wave at the desired voltage value. The steepness of the front is limited by the total load capacitance in combination with the generator inductance, the lead inductance, and the series resistance. The lower these

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