The emission life of oxide cathode tubes

Redhead, P. A.; McNarry, L. R.

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THE EMISSION LIFE OF OXIDE CATHODE TUBES

P. A. REDHEAD AND L. R. McNARRY

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ABSTRACT

A review of the causes of emission failure of oxide cathode tubes is presented. Part I discusses those parameters affecting tube life which are controllable, to some degree, by the circuit designer. Part II considers those parameters which are controllable only during the design and manufacture of the tube.

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INTRODUCTION

The wide use and increasing complexity of modern electronic equipment has created a maintenance problem of the first magnitude, and has necessitated the present emphasis on reliability in military and other equipment. The most unreliable component in electronic equipment, it is alleged, is the electron tube. This paper reviews the causes of emission failure of oxide cathode tubes; other causes of failure, such as mechanical faults, are not considered. The first part discusses the effect on emission life of some tube parameters which are controllable to some extent by the circuit designer. It is hoped that this discussion may assist the circuit designer to avoid some of the common abuses of electron tubes. The second part discusses those parameters affecting cathode life which are controllable only during the design and manufacture of the tube.

The average receiving-type tube has a sufficient store of active material in the cathode coating to provide satisfactory emission for 50,000 to 100,000 hours. Unfortunately, such lives are seldom realized in practice owing to the deterioration of emitting properties of the cathode caused by the action of various contaminants. Several reviews of oxide cathode theory and practice may be referred to for a detailed description of oxide cathode phenomena (1, 2, 3, 4, 5, 6, 7, 8).

Any investigation of the causes of emission failure presupposes the existence of suitable short-term tests to predict the emission life of experimental tubes. For experimental convenience such tests should not take longer than 1000 hours to perform. A test has been proposed by Metson which has been used successfully at the Post Office Research Station (London). In this test the tube is operated normally, and the saturated emission of the cathode is measured periodically at a reduced anode voltage of 5 volts (to prevent the formation of positive ions in the tube) and a cathode temperature of 700°K. The saturated emission normally rises at first to a maximum and then decreases slowly; if the emission at 3000 hours is greater than 50 per cent of the maximum, the tube is considered to have a good life expectancy.

PART I

EXTERNALLY CONTROLLABLE PARAMETERS

(a) ELECTRODE DISSIPATION AND CURRENT DENSITY

The excessive heating of electrodes, owing to high power dissipation, causes the evolution of sorbed gases or the decomposition of films on the electrode surface, which poison the emission of the cathode; thus tubes should be run well within their power ratings for long life expectancy. This consideration is modified when the electrode is made of a material whose "gettering" efficiency (i.e., the ability to sorb gases) is high at elevated temperatures. Such materials are tantalum (optimum temperature 1000°C), zirconium (1000°C to 1700°C), thorium (400°C to 500°C), "Ceto" (20 per cent mischmetal and 80 per cent thorium, optimum temperature 200°C to 500°C), and columbium (500°C). These bulk gettering materials are usually found in transmitting tubes. When the anode is made of such materials it is advisable to operate it near its optimum gettering temperature for long life.

If the coating has a finite resistance, a high cathode current density may result in an increase in the cathode temperature caused by the I^2R dissipation in the cathode coating. This increase in temperature will shorten tube life appreciably (see Part I (c)).

The current flowing through the cathode coating consists in part of an ionic current which causes gradual dissociation of the coating and hence affects cathode life. The time taken for complete dissociation of the coating is given approximately by

$$t_d = 2 \frac{d_c}{j_e k_i / k_e} \text{ hours,}$$

where d_c is the coating thickness in centimeters
j_e is the cathode current density in amperes/centimeter^2
k_i is the ionic conductivity
k_e is the electronic conductivity.

Using Isensee's (9) value of $k_i/k_e = 10^{-5}$
and $d_c = 5 \times 10^{-3}$ centimeters
$j_e = 10$ milliamperes/centimeter^2,
then $t_d = 100{,}000$ hours.

If the electrolytic dissociation is the prime cause of emission failure (other factors are normally more important in commercial tubes), then life will be inversely proportional to cathode current density.

(b) ANODE VOLTAGE

One factor causing poisoning is the bombardment of the cathode surface by positive ions (10). Positive ions may be formed by two main processes: either by collision of electrons with residual gas molecules, or by the breakdown under electron impact of any surface film on the electrodes. The first process starts when the electron energy exceeds the ionization potential of the residual gas, while the second process starts when the electron energy exceeds the heat of formation of the compound forming the contaminating layer on the electrode (11).

Since anode voltage is normally determined by circuit considerations there is little that the designer can do to reduce these effects. Operation at low anode voltage will increase emission life by reducing the amount of ionization to some extent. If circuit considerations allow the use of an anode voltage less than 10 volts, where ionization is negligible, greatly increased emission life and increased stability of characteristics may be expected from commercial-type tubes.

The solid curve in Fig. 1 shows the constant emission obtained with an anode voltage of 1.2 volts. The dashed curve shows the fall in emission observed with V_a = 200 volts and the grid voltage adjusted to give the same initial anode current. In the first case there is no ionization of residual gases in the tube. The two cases are comparable since both tubes were in the same envelope and hence at the same gas pressure.

Fig. 2 illustrates, very generally, the decrease in life expectancy with increased anode voltage. The operating anode voltage for these tube types increases approximately in this order: 6AL5, 6AK5, 2C26A, 6X5, 2X2, 1Z2. It may be seen that the failure rates of the various tube types increase with increasing anode voltage, with the exception of the 2C26A. These results are for tubes in normal use in electronic equipment and show failures due to all causes and not to emission failure alone; thus these curves are only indicative of a general tendency.

The above considerations are modified for tubes using bulk getter material, and which have been subjected to a rigorous outgassing and pumping schedule (e.g., many transmitting-type tubes).

It is difficult to show definitely that an increase in anode voltage decreases the life of the tube directly, since an increased anode voltage is usually accompanied by an increased anode dissipation, and thus a larger evolution of gas from the anode. However, there is no doubt that anode voltages below ionization potential result in very long life expectancy.

(c) CATHODE TEMPERATURE

Cathode temperature has a marked influence on poisoning of the cathode emission by residual gases. At high cathode temperatures the poisoning effect of these gases, in particular oxygen, is most rapidly compensated since the oxygen ions can readily diffuse through the coating to the cathode core and react with the free barium, thus affecting the cathode emission only slightly since poisoning is mainly a surface effect. At lower temperatures the rate of diffusion is greatly decreased since the diffusion coefficient is an exponential function of temperature, and finally at a low enough temperature the lattice defects "freeze in". Thus compensation for the effects of contaminating gases becomes more and more difficult at lower temperatures, and the poisoning effect of these gases increases (10).

Raising the cathode temperature decreases emission life primarily by increasing the rate of evaporation of barium from the cathode surface, and thus hastening the time at which the coating is exhausted of barium and emission failure occurs. This rate of evaporation increases exponentially with temperature (12). Fig. 2 is illustrative of the increase in the number of failures in a given time with increasing cathode temperature.

To summarize, it is highly undesirable to run cathodes at temperatures higher than optimum, and almost as undesirable to underrun them by too great an amount. For long life and stable operation tube heaters should be run from regulated supplies at optimum, or slightly below optimum ratings.

(d) BULB TEMPERATURE

An increase in the temperature of the glass bulb of an electron tube causes gases to be evolved which poison the cathode. The magnitude of this effect may be seen in Fig. 4, which shows the failure rate of miniature-type tubes at bulb temperature of 30°C and 175°C. The life expectancy of these tubes is reduced from 5000 hours at 30°C to 1000 hours at 200°C. Failures due to the effect of evolved gas on emission properties are negligible until 1000 hours of life, but increase rapidly thereafter. A detailed account of the evolution of gases from glass has been given by Dushman (13).

For long life and stable operation it is desirable to keep the operating bulb temperature as low as possible.

PART II

INFLUENCE OF INTERNAL CONTAMINANTS

RESIDUAL GASES

The presence of gases in vacuum tubes is the major cause of emission failure. These gases may be left in the tube after evacuation owing to inadequate processing schedules; they may be evolved during the tube's operation from the electrodes, insulators, or glass bulb; they may be formed by chemical reactions within the tube, or by the decomposition of surface films by electron bombardment. In high voltage tubes gases may be evolved from anode or cathode when voltage breakdown occurs.

Counterbalancing the evolution of gases by the above processes is the continuous removal of gas from the system by sorption at the getters and by "ionization clean-up". Gases are ionized when current is drawn and are driven into the anode or cathode surfaces depending on their charge, and thus the gas is removed from the inter-electrode space. The sorption of gas ions by the cathode coating usually results in poisoning of the emission.

Gas pressure in the tube is measured in terms of the vacuum factor, defined as the ratio of ion current to electron current. The vacuum factor decreases rapidly during the first few hours of tube operation and finally becomes constant at a value k_o. Fig. 5 is a curve of vacuum factor measured on a Type 12AX7 tube, and is illustrative of the general shape of these curves. Metson (14, 15) has proposed that the final value of k_o is determined mainly by a photo-electric current from the ion-collecting electrode produced by the soft X-rays generated by the ionizing electrons. An integral of the area under the portion of the vacuum factor curve above k_o is a measure of the quantity of gas sorbed by the getter and electrodes during initial operation. The value of this integral gives an approximate measure of the quantity of gas taken up by the cathode coating and of the gas liable to be evolved later from other electrodes. The gas current integral may be used as a measure of the probability of future emission failure caused by gas poisoning.

To obtain low ultimate pressure in the tube it is essential that good gettering efficiency be obtained; this subject has been investigated in detail by Wagener (16).

(a) Outgassing

Outgassing of electrodes is usually performed by heating the electrodes in vacuum prior to assembling the tube, and by high-frequency bombardment while the tube is being evaculated. Outgassing

is also achieved by electron bombardment of the electrodes during the evacuation schedule. It has been found when heating electrodes to the same temperature for the same time by the above three methods that electron bombardment is the most efficient means of outgassing. Outgassing schedules should be completed with the heating of electrodes by electron bombardment.

An analysis of the gases liberated from oxide cathode assemblies has been made by Jacobs and Wolk (17). The gases evolved during cathode decomposition and electrode outgassing were H_2, CO_2, CO, and smaller quantities of H_2O, O_2, and N_2.

A major source of gas is the glass envelope; data on the quantity and nature of the gases evolved on heating is quoted by Dushman (13, p. 509). The major component evolved is water with some carbon dioxide and traces of other gases depending on the type of glass used. An investigation by mass-spectrographic methods of the gases evolved from heated glass and ceramics has been made by Williams (18). Bombardment of the glass by positive ions is the most effective method of degassing glass, and will evolve gases that cannot be liberated by heating the glass to its softening point (19).

(b) Chemical Reactions

Hamaker (20) has shown that some glasses evolve HCl on heating to 400°C; this HCl combines with the cathode material to form Ba- or Sr-chloride. The chlorides subsequently evaporate when the cathode is heated and condense on the grid and anode. During operation of the tube the chlorides are decomposed by electron bombardment and the evolved chlorine poisons the cathode emission. The evolution of HCl may be prevented by rinsing the glass, prior to baking, with KOH solution.

On breaking open a vacuum tube in a damp atmosphere the characteristic smell of acetylene is observed. Mass-spectrographic tests have established that the gas produced is in fact acetylene, and measurements of the quantity of acetylene produced have been made. The acetylene is formed by the reactions

$$Ba + 2C = BaC_2$$

$$BaC_2 + H_2O = C_2H_2 + BaO.$$

The main source of barium carbide is the barium getters which are flashed at a temperature high enough for the barium to react with carbon impurities in the metal of the getter container. Further tests with bulbs containing a getter only, produced comparable quantities of acetylene when the bulbs were opened to a small quantity of water vapour and the resultant mass spectra observed. The quantity of acetylene produced checked approximately with the measured carbon content of the getter sleeves used in these experiments.

Barium carbide is stable at room temperatures; however, when a tube is operating, some water vapour is likely to be present within the envelope which will react with the carbide to produce acetylene. The acetylene may be decomposed on the hot cathode surface to form carbon deposits. These carbon films will increase the emissivity of the affected area and thus lower its operating temperature. Thus the carbon deposits will decrease the cathode emission both by increasing its work function and by decreasing its temperature. This effect will occur in an irregular fashion over the cathode surface and will increase the "patch" effect. (For further discussion on these effects see Ref. 21.)

(c) Electron Decomposition Products

During activation and processing of oxide cathode tubes, films of evaporated material condense on the cooler electrodes. These films usually consist of evaporated material from the cathode coating or reaction products of coating material with gases in the tube (e.g., $BaCl_2$, as mentioned previously). These films will break down under electron bombardment when the electron energy is in excess of the heat of formation of the bombarded compound. The gases liberated may then poison the cathode emission. The onset of emission poisoning as the electron energy increases is very marked, and has been used to determine the heat of formation of various compounds (11).

THE MECHANISM OF CATHODE POISONING

Poisoning is caused by residual gas ions or atoms entering the oxide coating, causing an increase in the work function and a decrease of emission. At pressures above 10^{-3} millimeters all gases will reduce cathode emission. At these high pressures the cathode coating is sputtered away by positive ions. The cathode temperature is also increased by ion bombardment, causing increased evaporation. These processes are important only in gas-discharge tubes.

At the pressures found in commercial-type high-vacuum tubes the poisoning process consists of chemical combination of the residual gases and the cathode coating. Oxygen has the greatest poisoning effect of any gas, since it may decrease the excess barium in the coating simply by occupying vacant oxygen sites in the crystal lattice of the cathode coating.

At moderately high oxygen pressures or low cathode temperatures poisoning is irreversible, i.e., the low value of emission remains after removal of the oxygen supply. The original emission can be recovered only by reactivating the cathode at a higher temperature than previously. Hermann and Krieg (22) showed that irreversible poisoning occurs even when the oxygen is un-ionized, by operating their test diode at a voltage below 10 volts.

At low oxygen pressures and normal cathode temperatures the poisoning is reversible; i.e., when the oxygen supply is removed the emission recovers without any special treatment of the cathode. This effect has been studied by Metson (23).

Reversible oxygen poisoning is dependent on the ease with which additional oxygen ions can leave the lattice vacancies that they occupy. If the oxygen molecules striking the cathode surface are transformed to O^- ions, they can occupy vacancies in the BaO lattice and decrease the free barium density, thus increasing the work function. Since the O^- ion is foreign to the lattice (which consists of Ba^{++} and O^{--} ions) it can escape readily when exposure of the cathode to oxygen is ended. The conversion of an O^- ion to an O^{--} is unlikely within the lattice since it is necessary to supply 11.1 eV to cause this transformation. The emission of O^- ions from the oxide coating has been observed by Sloane and Watt (24) using mass-spectrographic methods.

At the pressures and cathode temperatures found in tubes in normal use only irreversible poisoning would be expected from the above considerations. However, Hermann and Wagener (8, p. 271) have proposed that O_2^+ ions may be formed (ionization potential 12.5 volts) and enter the cathode coating. Energy would be set free during a conversion of the O_2^+ ions into O^- ions which could be used for the formation of O^{--} ions. The O^{--} ions would be stable in the lattice and cause irreversible poisoning. Although the number of O^{--} ions produced in this way would be small they would have an observable effect over long periods.

The poisoning effect of CO is due to its reaction with BaO to form barium carbonate while CO_2 reacts directly with free barium. Hydrocarbons dissociate at the cathode surface to form carbon which increases the work function. Water vapour produces a poisoning effect similar to oxygen (25). The effect of Cl_2 and HCl has been referred to earlier. Sulphur compounds are also strong poisoning agents and have been investigated by Stahl (26). Rare gases produce no poisoning effects though they will sputter the coating away at sufficiently high pressures.

INTERFACE EFFECTS

(a) Interface Formation

The activation of an oxide-coated cathode is assisted by reducing agents in the metal of the cathode sleeve (27, 28, 29). A solid state reaction (30) takes place at the interface between the coating and the base metal, during which the barium oxide is reduced and free barium is liberated. This reaction may proceed further,

depending on the nature of the reducing agent, to produce a final product at the interface between the coating and cathode sleeve which may have a harmful effect upon the emission life of the cathode. Table I lists some reducing agents and the resulting interface compounds.

To achieve easy activation most modern cathodes use small quantities of silicon as the reducing agent in the nickel sleeve. The resulting interface compound, barium-orthosilicate, (7, 29), is characterized by a greyish color and can be seen quite clearly in the areas where the oxide coating has flaked off the upper cathode of Fig. 6. Since this is the most common interface compound, and also the one about which most is known, the remainder of the discussion will be devoted to Ba_2SiO_4.

Eisenstein (7) has measured the interface thickness, by X-ray methods to be of the order of 10^{-3} cm., while Wright (27) has estimated that it is at least of the order of 10^{-5} cm. in thickness. The formation of the interface layer retards the rate of reaction between the silicon content of the sleeve and the barium oxide in the coating. This solid state reaction continues at a steadily decreasing rate throughout the active life of the cathode, thus limiting the thickness of the interface layer.

The formation of the interface layer may be controlled by the type of nickel used in the cathode (31). There are roughly three grades of nickel used: passive nickel which contains less than 0.01% silicon impurity; normal nickel containing 0.02 - 0.06% silicon; and active nickel whose silicon content is not greater than 0.25%. Passive nickel does not show any evidence of interface formation. The interface formed on normal nickel cathodes is not troublesome under class A operation but can develop appreciably under low duty factor operation. The interface formation on active nickel cathodes can develop appreciably under almost any condition of operation, becoming severe under low duty factor operation.

(b) Interface Behaviour

The interface behaves as an impurity semiconductor, and consequently its electrical properties are a function of its past history. At the conclusion of the activation process the interface has already been formed but its conductivity is high. Depending on the operating conditions of the tube the conductivity is modified throughout the life of the tube. Wright, Eisenstein, Nergaard and others (28, 30, 32, 33, 34, 35) have shown that operation under cutoff conditions is most conducive to the development of a high resistance interface. This effect is shown in Fig. 7 where it is evident that for normal heater voltages at 1000 hours the interface, under cutoff conditions, has a resistance six times as great as when cathode current is flowing.

TABLE I

CATHODE BASE METALS AND RESULTING INTERFACE COMPOUNDS

Base metal	Pt	Ni	Ni	Ni	Ni	Ni	Ni
Reducing Agent	none	none	Si	Ti	W	Mg	Al
Interface Compound	$BaPtO_3$	none	Ba_2SiO_4	Ba_2TiO_4	Ba_3WO_6	MgO	$BaAl_2O_4$
Resistivity	high	—	high	variable	low	low	low

The interface may be regarded as a leaky capacitor which has appreciable capacitance due to the thinness of the interface layer. If the dielectric constant is taken as 10 and the thickness as 10^{-4} cm., the capacitance per cm^2 is of the order of 0.01 mfd. The resistance may range from a few ohms to several thousand ohms in extreme cases. The major effect upon tube life is the gradual insertion into the cathode circuit of this parallel C-R network. The circuit designer, when dealing with tubes which may develop an interface impedance, should recognize that this impedance is frequency-sensitive and has a time constant of the order of 10^{-6} seconds. The resistance increases with life, while the capacitance decreases; thus there is little major change in the time constant (36).

The interface may cause sparking at high emission current densities. Eisenstein (7) and Wright (35) have shown that fields of the order of 5×10^5 volts can exist across the interface layer at current densities of 10 amp/cm^2. These fields approach those necessary to cause dielectric breakdown. When this occurs the coating may be disrupted at the location of the spark, and if the sparking continues, destruction of the coating can result with subsequent loss of emission.

The necessity of maintaining the cathode temperature below the value where an excessive amount of barium is evaporated is stressed in Part I (a). The I^2R heating of the interface resistance, which may reach an appreciable fraction of a watt, causes an increase in the coating temperature and in the rate of barium evaporation.

Fig. 7 shows the effect of cathode temperature on the rate of growth of the interface resistance. The increase of interface resistance with temperature is caused by the increased rate of the reaction forming the interface, thus further emphasizing the necessity of maintaining the correct cathode temperature. Interface conductivity is strongly temperature dependent, as shown in Fig. 8. Thus once the interface layer has grown to a relatively stable thickness, a short-term increase in its temperature causes an increase in interface conductivity. This conductivity change is reversible with temperature.

The interface may also be activated by the passage of current through the layer, which results in an increase in the conductivity. If the interface is regarded as an impurity semiconductor, with barium acting as the donor, there are two mechanisms which affect the conductivity. When no cathode current is flowing the equilibrium concentration of free barium ions in the interface layer is determined by the rate of thermal diffusion of the barium ions. However, when cathode current is flowing the electric field across the cathode induces a flow of barium ions into the interface layer. This electrolytic process, at normal current densities, exceeds the rate of thermal diffusion of ions out of the interface, resulting in activation of the interface.

The emission life of the cathode depends upon continual production of free barium in the coating. When the metal sleeve and the coating are separated by an interface layer of sufficient thickness, the production of free barium in the coating by the reaction between the reducing agent in the sleeve and the barium oxide is greatly reduced. This is substantiated by the fact that the growth of the interface thickness decreases with life, indicating a reduction in the rate of the solid state reactions at the boundary between the base metal and the coating.

(c) The Mechanical Interface

Raudorf (36) proposed a mechanical interface model to explain the variation of transconductance with tube life. He suggested that the contact between the coating and the base metal deteriorated during life and that this resulted in the formation of a parallel C-R network, with electrical characteristics similar to the chemical interface. Raudorf performed experiments to show that flat-type cathodes were superior to round cathodes in securing a good mechanical bond. During the spraying of the cathode the coating particles arrive in a direction normal to the surface for flat cathodes, and adhere better than in the case of round cathodes where the angle of incidence may vary from zero to 90 degrees.

The poor mechanical bond is rather rare but cannot be entirely neglected as a cause of emission failure. New tubes have been observed to have an interface impedance which was not temperature dependent, thus indicating an interface of the mechanical type. The upper 6AK5 cathode in Fig. 6 illustrates an extreme case of a poor mechanical bond.

BASE METAL EFFECTS

Impurities in the base metal have a marked effect upon the emission life of the oxide cathode. The impurity content of some commercially available cathode nickels is given in Table II. Kern and Lynch (37) have shown that for long life there is an optimum content of reducing impurities in the base metal regardless of the nature of these impurities. Emission is controlled by the concentration of free barium in the coating, the value of this concentration is established by the equilibrium between the formation of free barium, by reduction of barium oxide at the core, and the rate of evaporation of barium from the surface. At low impurity content the rate of formation of barium by reduction is small and the free barium content of the coating decreases steadily from its value after activation. With large impurity content the rate of production of free barium is increased; to maintain equilibrium the rate of evaporation of barium must also increase 8, vol. II, p. 283). Thus the store of barium in the coating is rapidly depleted and the end of life is reached earlier than at optimum impurity content.

TABLE II

CHEMICAL ANALYSES OF SEVERAL COMMERCIAL CATHODE NICKELS

Name of nickel	Percentage of other elements							
	C	Cu	Fe	Mn	Mg	Si	S	Ti
Grade A	0.20	0.20	0.30	0.35	—	0.20	0.008	—
INCO 220	0.15	0.20	0.20	0.20	0.01-0.10	0.1 -0.5	0.008	—
" 224	0.15	0.20	0.20	0.20	0.01-0.10	0.12-0.20	0.008	0.02
" 225	0.15	0.20	0.20	0.20	—	0.15-0.25	0.008	—
Driver Harris 499	0.05	0.04	0.05	0.02	0.01	0.01	0.005	—
" " 599	0.08	0.04	0.05-0.10	0.10	0.01	0.15-0.25	0.005	—
" " 699	0.08	0.04	0.05-0.10	0.10	0.05-0.15	0.05-0.15	0.005	—

Horak (38) has reported some recent work in which he investigated the emission properties of (i) a pure nickel cathode, (ii) a nickel cathode with 0.2% silicon, (iii) a nickel cathode with 4% silicon, and (iv) a nickel cathode with 4.7% tungsten. His results indicate that for (i) emission increased slightly up to 8000 hours, for (ii) emission increased up to 5000 hours then decreased, for (iii) emission decreased steadily up to 8000 hours, while for (iv) the initial emission density was higher than (i), (ii), and (iii) by a factor of 10 and remained constant up to 8000 hours.

Waymouth (32) has observed that cathode nickels which contain considerably less than 0.05% iron do not develop a high resistance Ba_2SiO_4 interface even under low duty factor operation. He postulated that the presence of $BaMnO_4$ in the barium orthosilicate lattice might provide permanent impurity centres. However, when iron is present, the strong oxidizing properties of the MnO_4^{--} ion will cause it to react with the iron and so reduce the number of impurity centres in the interface lattice.

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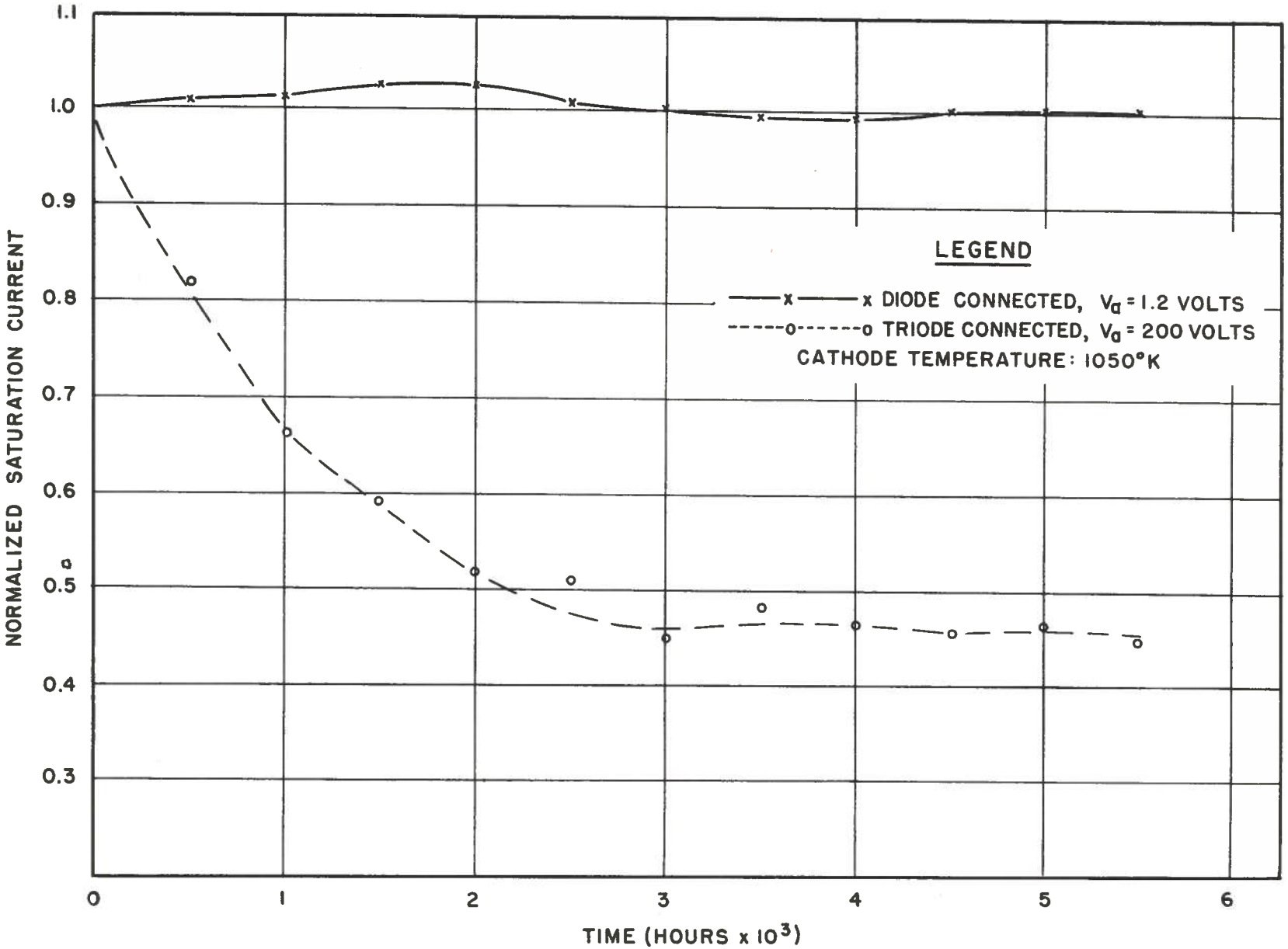


FIG. 1
EFFECT OF ION BOMBARDMENT ON CATHODE EMISSION

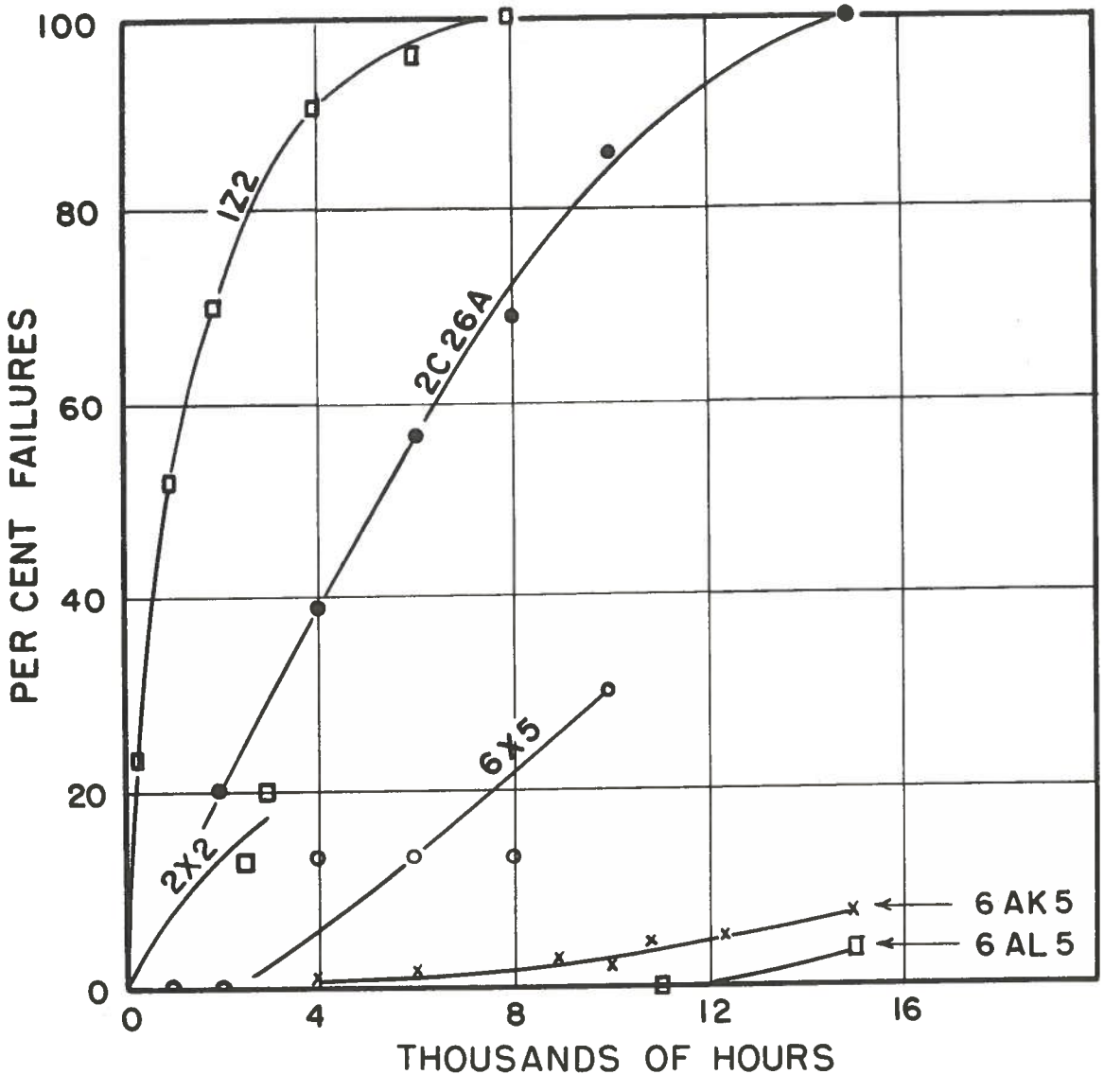


FIG. 2
RATE OF FAILURE OF TUBES IN ELECTRONIC EQUIPMENT

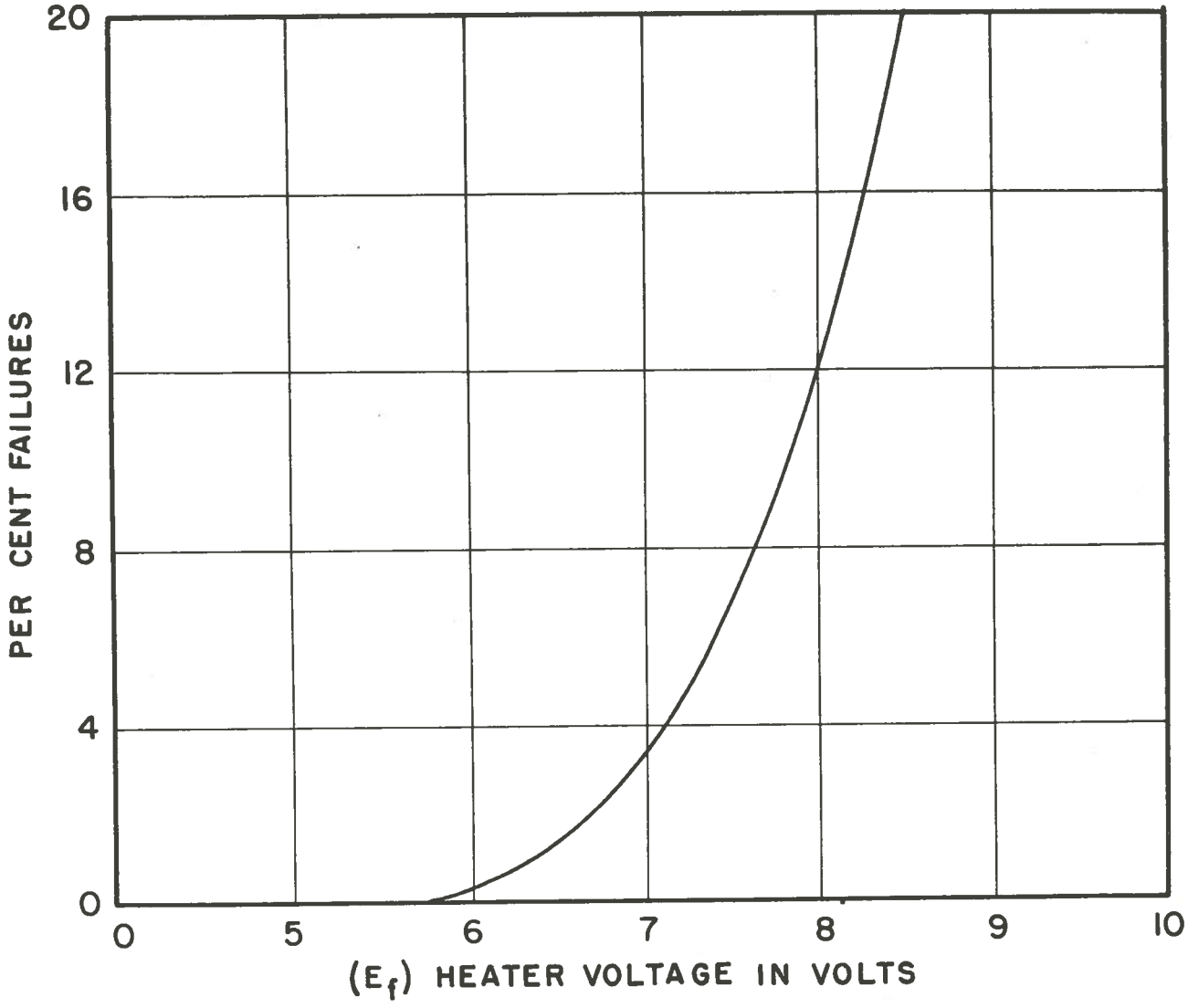


FIG. 3
RATE OF FAILURE VERSUS HEATER VOLTAGE FOR TYPE 6SN7-GT TUBE

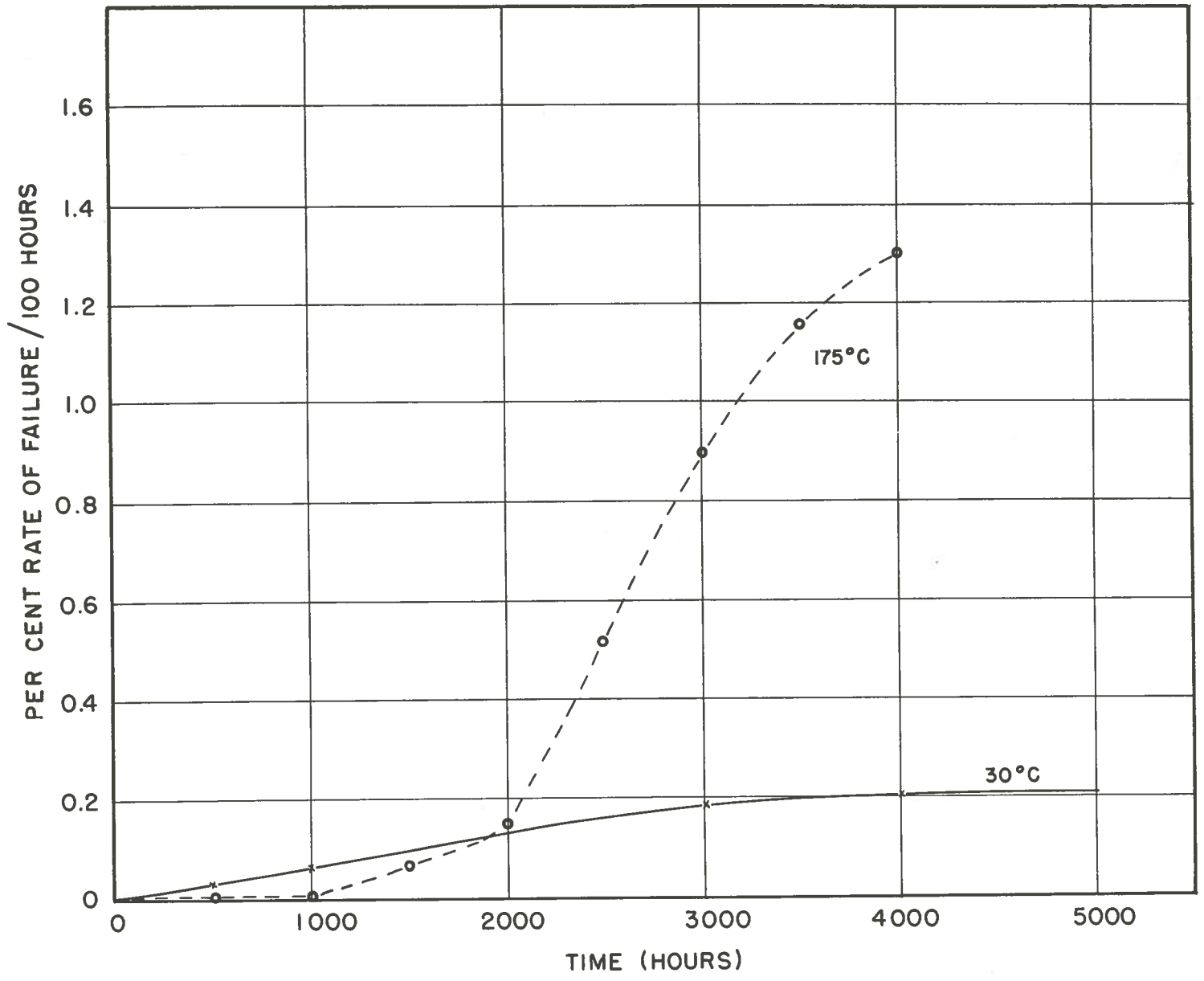


FIG. 4
RATE OF FAILURE OF MINIATURE TUBES FOR DIFFERENT BULB TEMPERATURES

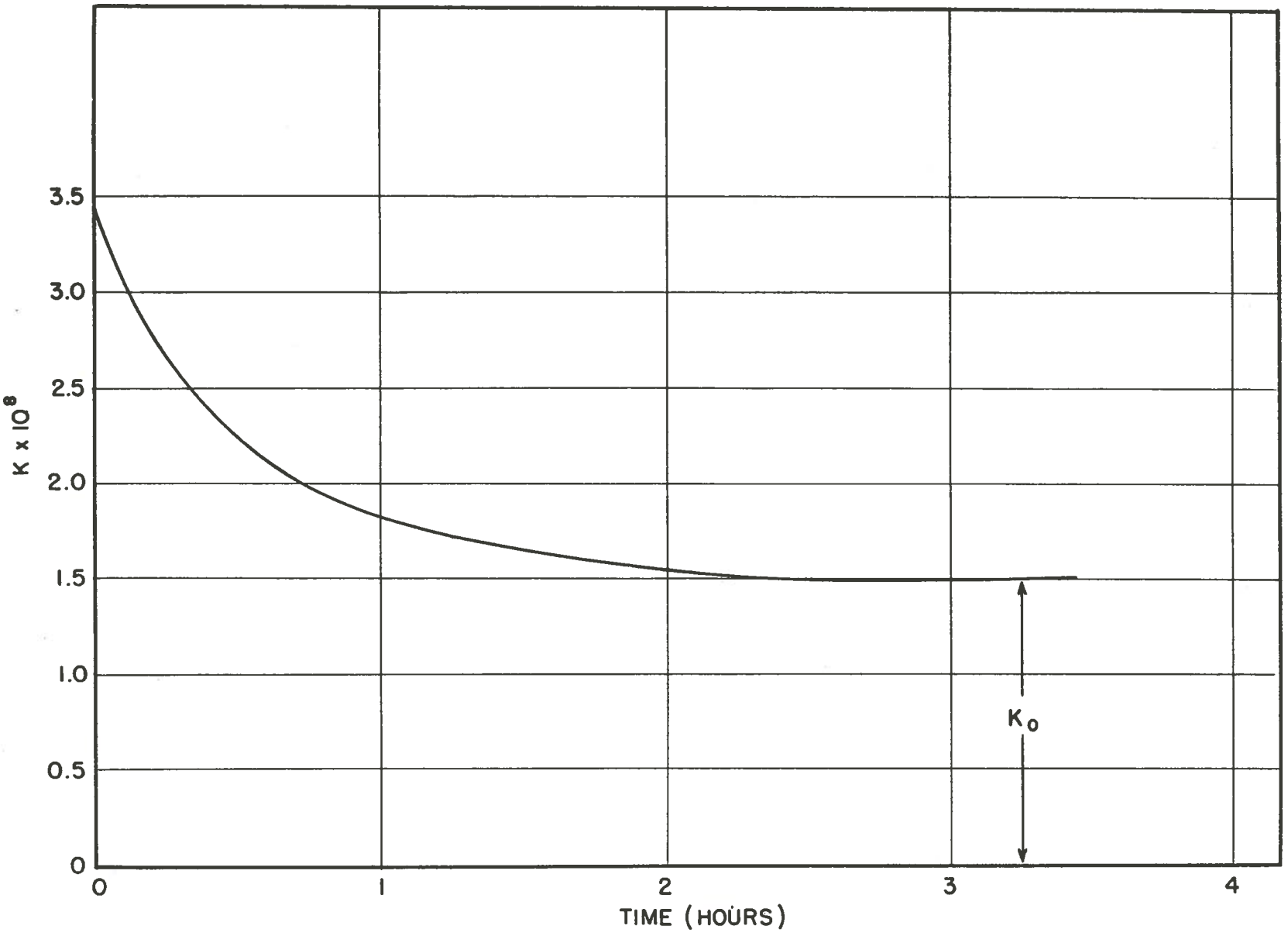


FIG. 5
CHANGE OF VACUUM FACTOR K WITH TIME FOR TYPE 12AX7 TUBE

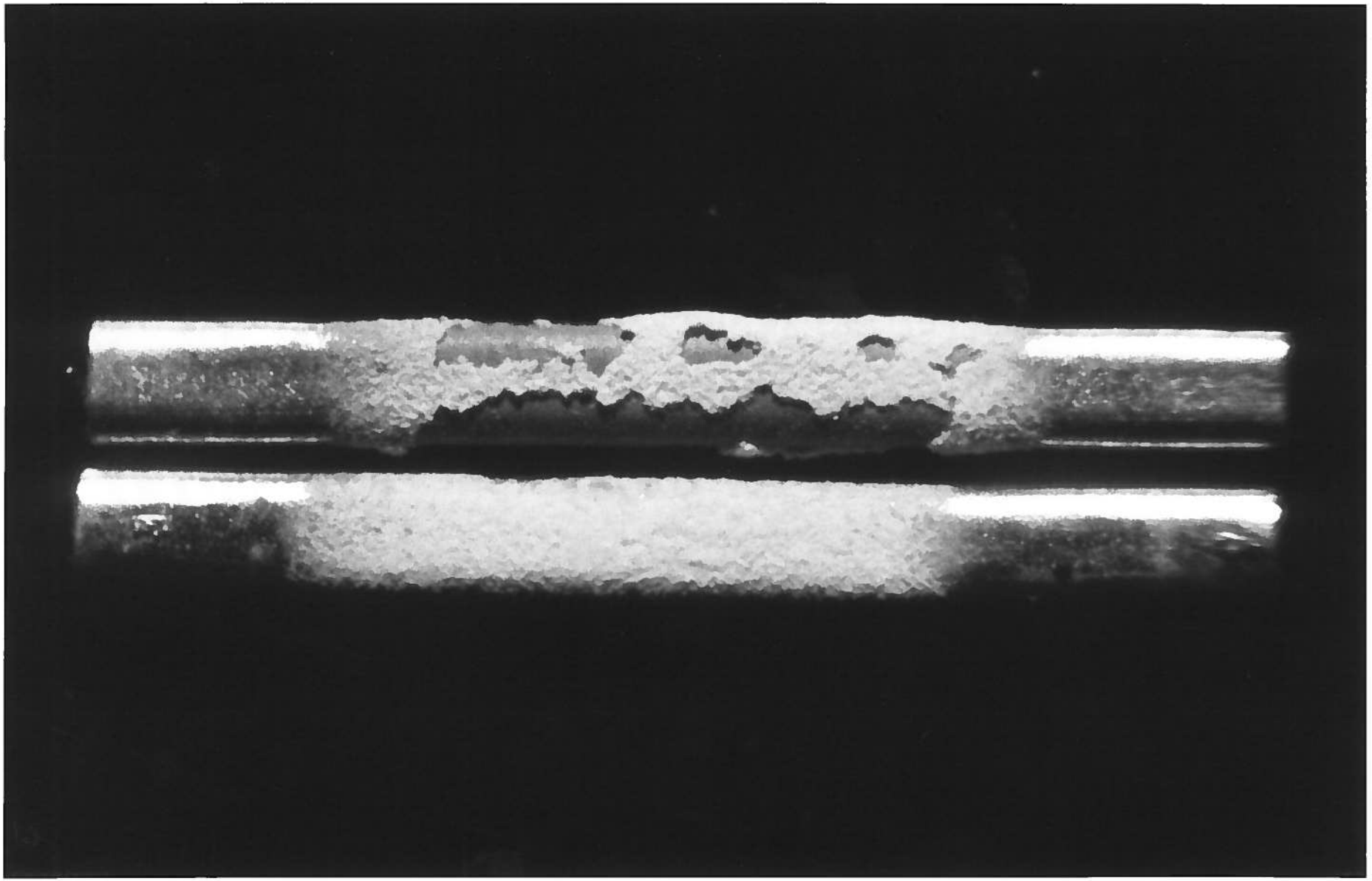
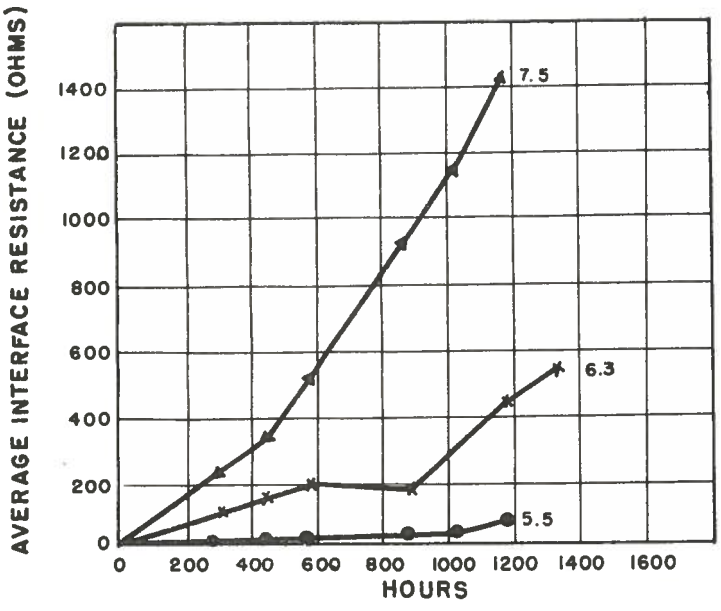
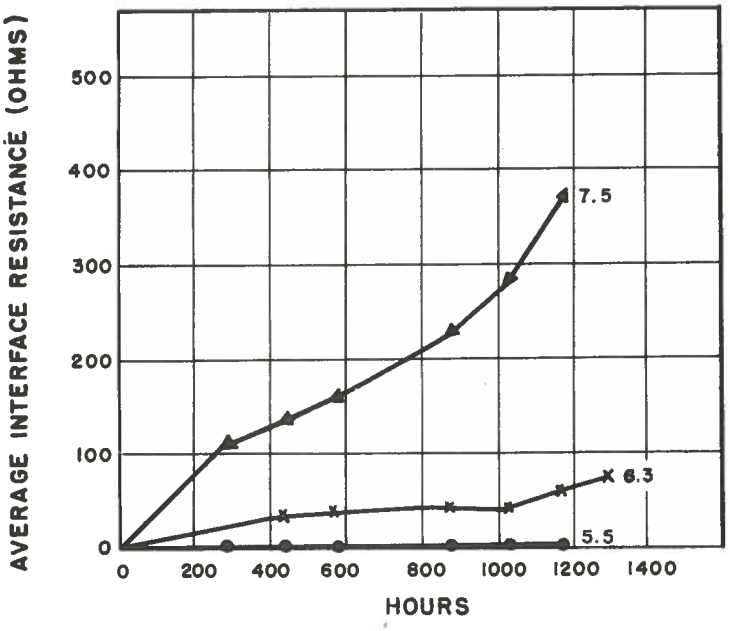


FIG. 6
TYPE 6AK5 CATHODES SHOWING FORMATION OF INTERFACE ON UPPER CATHODE



OPERATION UNDER CUTOFF CONDITIONS



CLASS A OPERATION
(BARTLEY AND WHITE [33])

FIG. 7
RATE OF GROWTH OF INTERFACE RESISTANCE

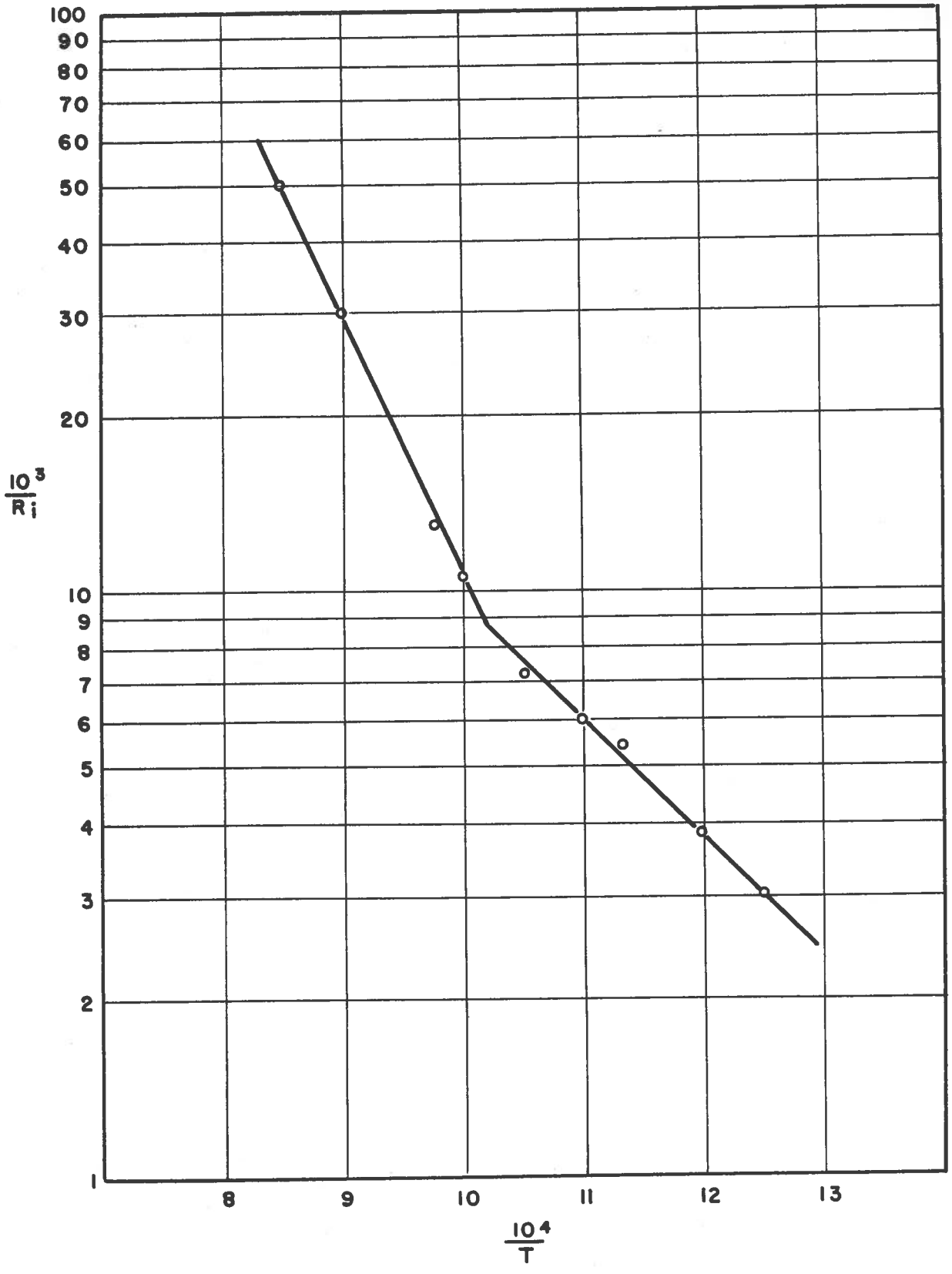


FIG. 8
TEMPERATURE DEPENDENCE OF INTERFACE CONDUCTIVITY