The Effect of Temperature, Degree of Thoriation and Breakdown on Field Currents from Tungsten and Thoriated Tungsten

A. J. AHEARN, *Bell Telephone Laboratories*

(Received June 1, 1936)

Electron field currents from thoriated tungsten, with different degrees of thoriation, were found to be independent of temperature. The characteristic field current curve was found to be independent of the degree of thoriation of a thoriated tungsten filament. An electrical breakdown, a sudden discontinuity in the characteristic field current curve at which the current increases from small values usually considerably less than a microampere to a few milliamperes, occurs with thoriated tungsten and pure tungsten cathodes. This breakdown raises the field current curve to higher currents by an enormous factor. Current increases by factors from 10,000 to 10,000,000 were usually obtained. With pure tungsten no change in the thermionic activity of the cathode results from the breakdown; with thoriated tungsten the thermionic emission is increased; i.e., a partial thoriation of the filament occurs. Heat treatment at about 1300°K following breakdown generally further increases the field currents from thoriated tungsten but produces no such effect with pure tungsten. The high field currents following breakdown can be erased by heating the cathode to about 2600°K for a few minutes. The value of the breakdown field is independent of the temperature and the degree of thoriation of a thoriated tungsten cathode. The application of the usual breakdown voltage with the filament as anode produces none of the usual effects of breakdown. Breakdown does not occur if a sufficiently high resistance is inserted in the circuit. In general, successive breakdowns occur at increasingly higher values of the applied field. None of this progression can be attributed to a conditioning of the anode. A definite part of this progressive increase in the breakdown field can be attributed to glass surfaces when they are exposed to the discharge. The highest electric field that could be applied to a cathode without breakdown occurring was about 4.7×10^6 volts/cm. The evidence favors the following conclusions: The electric field applied to the cathode rather than the applied voltage is the more important factor in producing breakdown. The anode has no effect on the breakdown. When the shielding of glass surfaces is adequate, the breakdown is determined primarily by conditions at the cathode.

INTRODUCTION

MANY years ago it was discovered that electrons are emitted from a seemingly cold cathode when a sufficiently high voltage was applied. There was at first some question whether the onset and subsequent rise of this "cold discharge" depended primarily on the applied potential or upon the electric field applied to the surface of the cathode. Later experiments, in which the electrode separation in a given tube could be varied at will, showed definitely that the discharge was determined by the applied electric field at the cathode rather than by the applied voltage. For this reason this cold discharge of electrons is designated quite frequently by the term "field currents."

In field current experiments small fluorescent spots are often observed on the anode. By means of a magnetic field they can be moved about. This shows that field currents are not emitted uniformly over the surface of the cathode but consist chiefly of pencils of electrons from a few minute areas. These active areas probably consist of surface irregularities such that the applied electric field is there much greater than the average value over the surface of the cathode.

Whereas a thermionic current increases *very slowly* with the applied field, the logarithm of the current being proportional to the square root of the field in the Schottky effect, the field current emission varies very rapidly with the applied field. The functional relationship between current and field is quite different from that of the Schottky effect. Here the logarithm of the emission is proportional to the reciprocal of the applied field. Thus the variation of field currents with the applied field is of exactly the same form as the variation of thermionic currents with temperature.

The earliest experiments agreed that there was no large effect of temperature on field currents. It was found that the measured current remained unchanged as the temperature was raised from room temperature to about 1000°K. However, it was observed that a further increase in temperature to 1100°K resulted in an increase in the measured current by about 30 percent. One school of investigators interpreted this as a real field current temperature effect while others maintained that this increase was due merely to the onset of the thermionic emission. It has since been definitely established that, when the thermionic emission correction is properly made, there is no evidence whatever for any effect of temperature on field currents from clean surfaces of tungsten and molybdenum. In view of the experimental fact that field currents from clean surfaces of metals are independent of temperature, it is important to know whether or not this independence extends to the case of composite surfaces. To this end temperature experiments were made with thoriated tungsten and are presented in Part I of this paper.

Little work has been done on the effect of the work function of the cathode on the field currents therefrom. In work of this kind it is important to be able to alternately increase and decrease the work function of the cathode by sizable amounts in order to distinguish between a real effect of the work function and a simple aging of the filament. Experiments of this sort are described in Part II.

In general, once a given field has been applied to a filament, so long as this value is not exceeded, a reversible current *vs.* field curve is obtained. When this value of the field is exceeded a new reversible curve results usually corresponding to somewhat smaller current values. However, when the applied field is extended to 1 or 2×10^6 v/cm a sharp discontinuity occurs involving enormous changes in the field currents. Experiments dealing with these breakdown effects are described in Part III.

PART I

The Effect of Temperature on the Emission of Electron Field Currents from Thoriated Tungsten

Introduction

In an earlier publication[1] results on the effect of temperature on the emission of electron field currents from molybdenum and tungsten were presented. In this work, the thermionic emission, particularly its onset, was separated from the field current emission by extrapolating high temperature emission measurements. Extensive measurements over a wide range of conditions showed that: (1) between 300°K and 1400°K, at which temperature the thermionic emission became perceptible, the electron field currents are independent of temperature to within 5 percent; (2) between 1400°K and about 1600°K the data are consistent with the assumption that the measured current consists of the thermionic current plus the field current which is independent of temperature; (3) beyond about 1600°K the field currents were completely masked by the thermionic currents. Thus from clean surfaces of tungsten and molybdenum there is no evidence of any field current temperature effect as great as 5 percent.

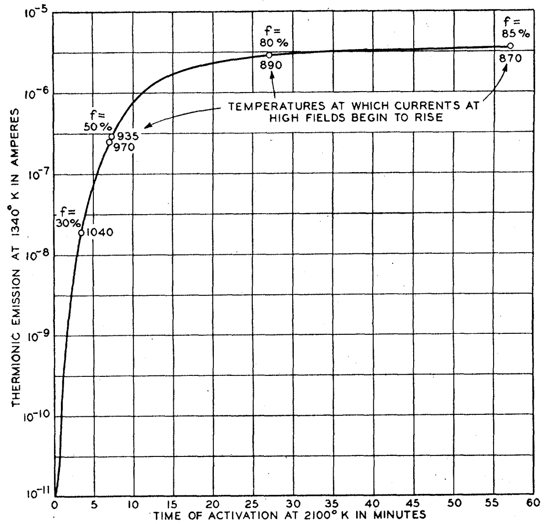

FIG. 1. Thermionic activation of thoriated tungsten filament. Field current *vs.* temperature measurements were made at the indicated points on the curve, the thermionic current becoming perceptible at the indicated temperatures.

Results

In this section, using the same technique of measurement and analysis of data, results on the effect of temperature on electron field currents from thoriated tungsten are presented. The filament was flashed at about 2800°K and then activated by operating at about 2100°K for about 60 minutes as shown in Fig. 1. This served to raise the thermionic emission at 1340°K by a factor of about 400,000. At the different states of activation[2] given by the plotted points in Fig. 1,

[1] Ahearn, Phys. Rev. **44**, 277 (1933).

[2] In this paper the degree of thoriation is given by values, reference 3, of f which are *approximately* proportional to the percentage of surface covered with thorium.

[3] Brattain and Becker, Phys. Rev. **43**, 428 (1933).

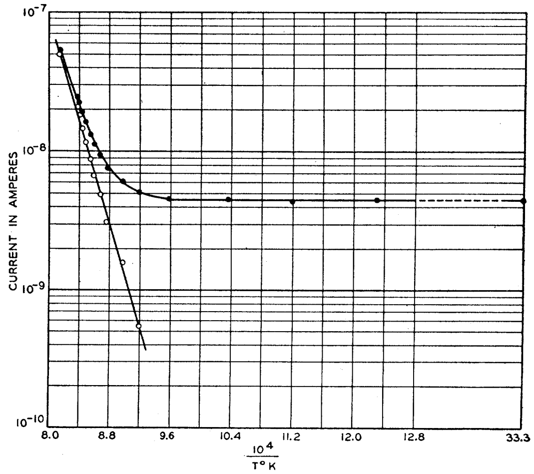

FIG. 2. Emission current *vs.* temperature data for thoriated tungsten filament. $F=5.7\times10^5$ v/cm. $f=28$ percent.

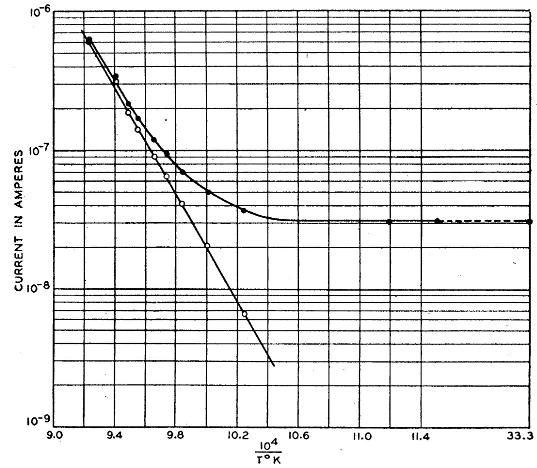

FIG. 3. Emission current *vs.* temperature data for thoriated tungsten filament. $F=9.3\times10^5$ v/cm. $f=80$ percent.

for different values of the applied field, emission current *vs.* temperature measurements were made. In all, measurements were made in the range of applied field from 4.4×10^5 volts/cm to 9.3×10^5 volts/cm. Figs. 2 and 3 give typical sets of data and show the effect of temperature. In Fig. 2 one sees that the measured currents are independent of temperature up to about 1040°K. The points marked by open circles (○) are obtained by subtracting the room temperature value of the field current from the observed currents at the higher temperatures. If the field current is independent of temperature these difference currents should be the values of the thermionic emission and should therefore, according to the Richardson thermionic emission law, fall on a straight line. They do satisfy a straight line relation very well as shown and one can assume that the increase in the observed current is due entirely to the thermionic emission. The data of Fig. 3 and all similar data taken at the various points on Fig. 1 show the same result.

Summary

The results therefore may be summarized as follows: Measurements were made over the range of applied field from 4.4×10^5 v/cm to 9.3×10^5 v/cm. The degree of thoriation f as varied from about 30 to 100 percent. At temperatures, indicated at the different points of Fig. 1, below which the thermionic emission is imperceptible, the field current (i.e., the measured current) is independent of temperature to within 5 percent. Over the temperature range employed, where the thermionic current does contribute to the measured emission, the data are all consistent with the assumption that the field current is independent of temperature. Thus, in complete agreement with the results on clean surfaces of molybdenum and tungsten, there is no evidence for any field current temperature effect with thoriated tungsten.

PART II

The Variation of the Field Current Characteristics with the Degree of Thoriation of Thoriated Tungsten

Introduction

Having found that, so far as the effect of temperature of field currents was concerned, thoriated tungsten was not unlike clean tungsten and molybdenum, it was of some interest to see how the field current characteristics varied as the thermionic work function of the thoriated tungsten was varied. This point was studied by measuring the field current characteristic, i.e., the field current *vs.* applied field curve, of one mil thoriated tungsten filaments where by the proper heat treatment different amounts of thorium were accumulated on the filament surface thus varying its work function. The experimental tube is described elsewhere.[1]

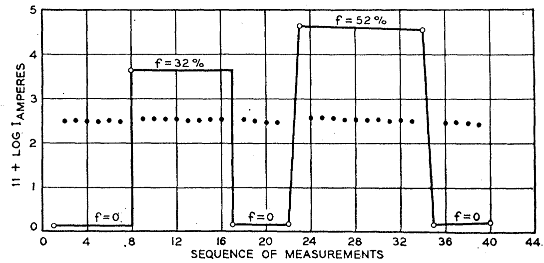

FIG. 4. Field current *vs.* degree of thoriation data for thoriated tungsten filament. ○—thermionic current at 1340°K; ●—field current at 300°K and $F=6.5\times10^5$ v/cm. Field current measurements at 30 second intervals.

Results

Typical results are given in Figs. 4 and 5. In Fig. 4, the filament was flashed at about 2800°K for a few seconds after which a thermionic current of about 1×10^{-11} ampere was obtained at 1340°K as shown by measurement No. 1. This current is about the value characteristic of clean tungsten and it can be assumed that now the filament surface is nearly free of thorium, i.e. f is about equal to zero percent. The filament was then cooled to room temperature and a field of 6.5×10^5 v/cm applied, several current measurements being made at about 30-second intervals. Next by the appropriate heat treatment of the filament, enough thorium was accumulated on the surface to increase the thermionic emission by a factor of about 4000, i.e., f equals 32 percent as shown by measurement No. 8. Another series of field current measurements was then made. These are shown by points 9 to 16. By the proper heat treatment, the thermionic emission was now reduced to the original clean tungsten value and the cycle of measurements was repeated. In this case the thermionic emission was increased by a factor of about 40,000 i.e., f equals 52 percent. One immediately sees that the enormous changes in the thermionic activity are accompanied by little or no change in the magnitude of the field current. The average value of the field current corresponding to the low thermionic activity is 3.0×10^{-9} ampere ±5 percent while that for the high thermionic activity is 3.5×10^{-9} ampere ±5 percent. In view of the average deviations given, it is uncertain that this 16 percent increase is significant. The data do show that the field currents are nearly constant and independent of the degree of thoriation from f equal to 0 to about f equal to 50 percent.

TABLE I. *Constants of field current characteristic (log I vs. 1/f at 300° K).*

f in %	Slope		Intercept Current in amperes at $1/F=1.1\times10^{-6}$ cm/volt	
0		−2.63		3.5×10^{-8}
72	−2.53		3.0×10^{-8}	
0		−2.56		2.9×10^{-8}
0		−2.65		3.5×10^{-8}
43	−2.56		3.2×10^{-8}	
0		−2.63		2.9×10^{-8}
0		−2.67		3.5×10^{-8}
64	−2.72		3.6×10^{-8}	
0		−2.98		3.7×10^{-8}
Averages and average deviations	−2.68±3%	−2.69±4%	3.3±6%	3.3±9%

Table I summarizes further measurements on the same filament in which current *vs.* field measurements were made with widely different states of thermionic activity. The slopes and intercepts of the straight lines which result from plots of the logarithm of the emission *vs.* the reciprocal of the applied field are given along with the percentage of the surface covered with thorium. The filament is thermionically activated and deactivated repeatedly, through the values of f given. The average values for the slopes and for the intercepts of the field current character-

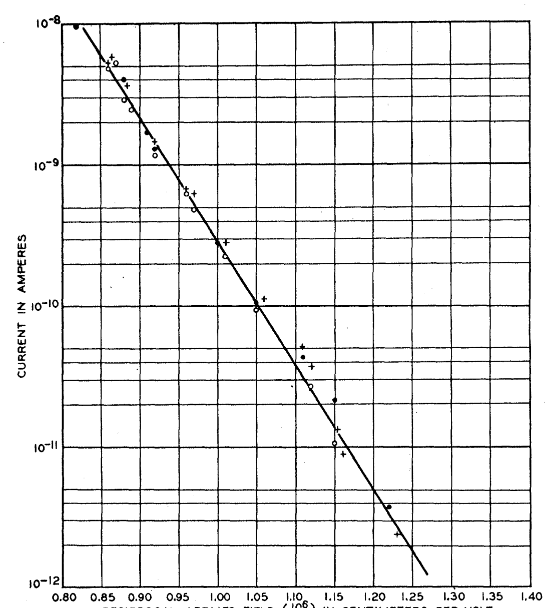

FIG. 5. Field current *vs.* applied field data as a function of degree of thoriation. Run 1 (●) $f=100$ percent; Run 2 (○) $f\sim0$ percent; Run 3 (+) $f=73$ percent.

istic curves accompanying the high thermionic activity state are not significantly different from those for the case of clean tungsten thermionic activity. Thus the field current independence of thermionic activity at the particular value of the field shown in Fig. 4 is shown to be quite general over the range of field investigated in Table I.

Fig. 5 shows similar results obtained with another one-mil thoriated tungsten filament. In Run 1 the filament is thoriated to f equals 100 percent. In Run 2 (f equals 0), a nearly clean surface of tungsten is presented. Again in Run 3, by the appropriate heat treatment, the filament is again thoriated to f equals 72 percent. The single straight line satisfies the three sets of data reasonably well.

The data of Fig. 4 show that at a given value of applied field, the field current is, to within a few percent, independent of the degree of thoriation of the cathode. The data of Table I and Fig. 5 show that this independence holds quite generally over the entire range of applied fields studied and for all values of f from zero to 100 percent or to fully thoriated tungsten.

Discussion of results

This experimental fact that the field currents from thoriated tungsten are independent of the degree of thoriation of the filament can be interpreted in three different ways: (1) The field currents are independent of the work function of the emitting surface; (2) the minute areas which emit the field currents never become thoriated; i.e., throughout the cycle of experiments these areas are clean tungsten surfaces; (3) these minute areas originally become thoriated and in the above cycle of experiments they remain unchanged. Interpretation No. 1 if proved to be correct is of fundamental importance in any theory dealing with the mechanism of field emission. If interpretation No. 2 or 3 is correct then the results are significant only in a more practical way.

One might hope to choose between the last two cases by comparing the field current curves for the thoriated tungsten filaments with those for pure tungsten. The second interpretation would be favored if the field current characteristic curves for the two metals were about the same, but if there was a significant difference appropriate to the difference in the work function of thoriated tungsten and clean tungsten, then the third interpretation would be favored.

In practice, such a comparison of field current curves for different metals can be very deceiving. The two thoriated tungsten filaments studied gave widely different characteristic curves. Likewise different pure tungsten filaments gave different characteristic curves. Moreover the characteristic curve for a given pure tungsten filament varied through a considerable range depending on its treatment. Hence from the present work it is not possible to state whether the characteristic curves for the two metals are the same or are significantly different.

These experimental observations are not in agreement with somewhat similar work of other investigators. Gossling,[4] De Bruyne,[5] and Stern, Gossling and Fowler[6] found that with tubes in which the anode was coated with sodium phosphate or barium azide the passage of a glow discharge, i.e., the bombardment of the cathode by ions of sodium or barium, tends to increase the field current emission. This current increase is attributed to a decrease in the work function of the cathode due to the adsorption of the ions. It was implicitly assumed that the ion bombardment resulted in no pitting of the cathode surface. Stern, Gossling and Fowler explicitly assumed that this ion bombardment produced no change in the potential gradient form factor of the cathode. On this basis, they associated the shift of the field current curves with changes in the work function of the cathode due to adsorption of sodium or barium. No direct measurements of work functions or work function changes were made in any of these experiments. The observed shifts in the field current curves can be equally well explained by changes in the potential gradient form factor of the cathode due to pitting, etc. Therefore proof that field currents depend on the work function of the cathode is lacking.

Unpublished experiments by Langmuir, Dushman and Hull[7] are briefly described in which, with an activated thoriated tungsten filament

[4] Gossling, Phil. Mag. **1**, series 7 (1928).

[5] De Bruyne, Phil. Mag. **7**, series 5 (1928).

[6] Stern, Gossling and Fowler, Proc. Roy. Soc. **A124**, 699 (1929).

[7] Compton and Langmuir, Rev. Mod. Phys. **2**, April (1930).

with 30 kv applied, small field currents are emitted, which are rapidly increased to a much greater value by the thermionic emission resulting from the heating of the anode and the resulting back radiation. This effect apparently does not occur with an unactivated thoriated tungsten filament. It is not clear however that this is evidence that field currents from a thoriated tungsten filament are a function of the degree of thoriation, due to the confusing effect of the thermionic emission which varies so rapidly with the degree of thoriation.

Quarles[8] using a high frequency impulse voltage method measured the electric field needed at the surface of a mercury cathode to initiate a vacuum spark which is known to be initiated by field currents. The contact potential between the mercury cathode and a platinum filament was varied in an uncontrolled way through about 0.7 volt. The assumption is made that the work function of the platinum filament remained constant and that the contact potential changes therefore represent changes in the work function of the mercury surface. On this basis, it is found that the field necessary to initiate the vacuum spark increased linearly with these increases in the work function of the mercury surface. Earlier experiments by Beams[9] show that the breakdown potential with a mercury cathode depended on the purity of the surface.

Subject to a possible uncertainty in the interpretation of the contact potential changes the experiments of Quarles show fairly definitely that the field required to produce a vacuum spark which is known to be initiated by field currents, varies with the cathode work function. It follows from this that field currents from the mercury cathode depend on the work function thereof *only* if they comprise the entire cathode emission that is responsible for the vacuum spark.

Thus we have so far no clear cut case showing whether or not field currents are a function of the cathode work function. Information on the proper interpretation to be applied to the author's experiments could doubtless be obtained by depositing a few or several layers of thorium, or other suitable element, from an external source onto the cathode surface. If as suggested earlier,

[8] Quarles, Phys. Rev. **48**, 260 (1935).
[9] Beams, Phys. Rev. **44**, 803 (1933).

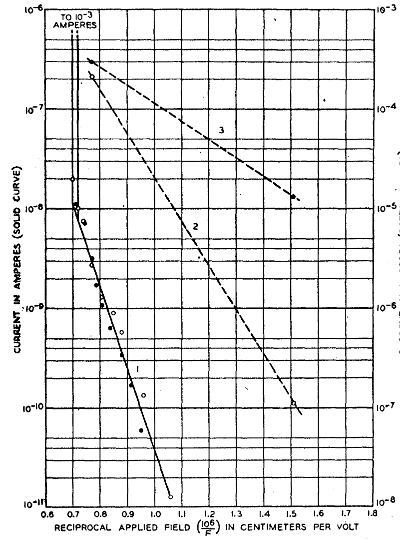

FIG. 6. Field current *vs.* applied field data for thoriated tungsten showing breakdown. Curve 1 (○) $f=4$ percent; Curve 1 (●) $f=0$ percent; Curve 2 (○) $f=20$ percent; Curve 3 (●) $f=13$ percent. 1.0×10^5 ohms resistance in anode circuit.

the negative results of the present experiments occur because the field current emission areas did not become thoriated, one might succeed in thoriating them in this way.

It seems very likely that using the electron microscope one could determine whether the areas active in field current emission were thoriated or were clean tungsten and whether or not they remained unchanged in the thoriation and dethoriation cycles of the above experiments. One could then choose between the above three interpretations of the experimental fact that the field currents are independent of the degree of thoriation of the filaments.

PART III

ELECTRICAL BREAKDOWN WITH THORIATED TUNGSTEN AND PURE TUNGSTEN

Description of breakdown

In extending the experiments on the effect of thoriation in the last section to higher fields a sharp discontinuity occurred as illustrated in Fig. 6. Between 1.0×10^6 v/cm and 1.3×10^6 v/cm the curve 1 was reversible but at 1.4×10^6 v/cm the current suddenly rose from 1×10^{-8} ampere to about 1×10^{-3} ampere. This discontinuity in the field current characteristic curve will be referred to as a "breakdown." On reducing the field, curve 2 is obtained which is approximately reversible. Noting the different current scales for curves 1 and 2, one sees that the breakdown has resulted in raising the characteristic curve by the enormous factor of 100,000 or more. Reducing the applied field to zero and heating the filament to about 2650°K for 40 seconds reduced curve 2 back to curve 1, the original pre-breakdown value. Again a reversible curve was obtained until a field of about 1.4×10^6 v/cm was applied at which point breakdown again occurred, the field current rising from about 1×10^{-8} ampere to about 1×10^{-3} ampere. The characteristic now given by curve 3, the currents being as much as 10,000,000 times greater than before breakdown. Heating the filament at 2650°K for a short time again reduced curve 3 approximately to that of curve 1.

Before the data of curve 1 were taken, a thermionic measurement showed that f equaled 4 percent approximately, i.e., the filament was only very slightly thoriated. Further tests showed that this value of f remained unchanged before the first breakdown occurred. However after this breakdown, the value of f was increased to 20 percent. In other words, now the thermionic emission at 1340°K was about 500 times greater than that of clean tungsten. The 2650°K heating of the filament employed to reduce curve 2 to curve 1 also reduced the value of f to about zero. Again, before breakdown, the thermionic emission remained unchanged but after breakdown the value of f was raised to 13 percent.

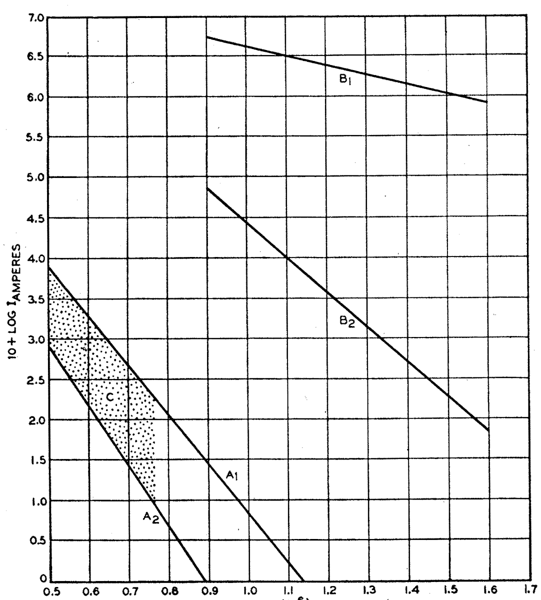

FIG. 7. An example of the range of breakdown fields and field current curves for a thoriated tungsten filament.
A_1 to A_2 Range of field current curves before breakdown.
B_1 to B_2 Range of field current curves after breakdown.
C The fields at which breakdown occur and the field currents just before breakdown fall in this dotted area.

Thus the breakdown produces two effects. It raises the field current characteristic curve on the current axis by an enormous factor. It increases the thermionic activity of the cathode by substantial amounts. Experiments with pure tungsten described later do not give an increase in thermionic activity following breakdown. Hence it follows that the increase with thoriated tungsten is due to a partial thoriation.

Range of field current increase following breakdown

In Fig. 6 one sees that the second breakdown shifted the characteristic curve 3 to higher current values than curve 2 which followed the first breakdown. One must not conclude however that successive breakdowns shifted the characteristic curve to increasingly higher current values. Many cases of breakdown have been observed in which the observable conditions were identical, i.e., the same characteristic curve before breakdown, the same breakdown field and current, the same thermionic activity of the filament, etc. Nevertheless the characteristic curves after successive breakdowns would be scattered at random over a wide range. Fig. 7 shows the range over which the curves after breakdown varied for a thoriated tungsten filament from which the data of Fig. 6 were obtained. In all about fifty breakdowns were observed with this filament before it was broken by a breakdown. For the same series of breakdowns the range of variation of the characteristic curve before breakdown is also given in Fig. 7. This variation did not proceed in any regular way with successive breakdowns but was quite random.

Neglecting the relatively small range over which the curve before breakdown varied, one sees that following breakdown, the characteristic curve may be raised to higher currents by a factor

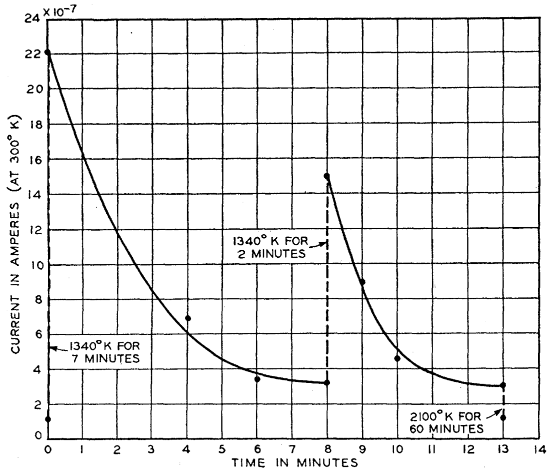

FIG. 8. Field currents from thoriated tungsten at $T=300°K$ and $F=6.5\times10^5$ v/cm.

anywhere between about 10,000 and about 1,000,000.

Degree of thoriation affected by breakdown

Just as there was wide variation in the amount by which the characteristic curve in Fig. 7 was shifted to higher currents by the breakdown, so there was considerable variation in the degree of thoriation produced by the breakdown. Whereas with f equal to zero before breakdown, it was found to range anywhere between zero and 50 percent after breakdown, values of f between 12 and 23 percent being most common. This must not necessarily be interpreted to mean that this thoriation is uniformly distributed over the surface. The above most commonly obtained values of f would be explained merely by assuming that 0.01 percent to 0.1 percent of the filament surface became fully thoriated by the breakdown.

There was no correlation between the magnitude of the thermionic activity increase and that of the field current curve shift to higher currents.

The effect of heat treatment of filament after breakdown

In connection with Fig. 6 it was stated that after each of the two breakdowns the characteristic curve was reduced to the low current values obtained before breakdown simply by heating the filament to 2650°K for less than a minute. This result could sometimes be attained at much lower temperatures. In a very few cases a temperature of 1340°K for a few minutes was sufficient. In many cases 2100°K for a minute or so was enough. In practically every case a temperature of about 2600°K for a couple of minutes was sufficient to restore approximately the characteristic curve obtained before breakdown.

A typical curve for the effect of low temperature heating of the thoriated tungsten cathode after breakdown is shown in Fig. 8. 1340°K for seven minutes raised the field current by a factor of about twenty. Leaving the voltage on, however, erased most of this gain. Again heating at 1340°K for two minutes gave an increase by a factor of five but the current decayed rapidly. In contrast to the increase in field current following the 1340°K heating, a temperature of 2100°K for one hour reduced this current slightly. A still higher temperature treatment in this case was necessary to reduce the current to the prebreakdown value.

Similar low temperature treatments at 1340°K and 1640°K of a pure tungsten filament after breakdown gave no increase in field current. As stated already, treating the thoriated tungsten filament at 1340°K *before breakdown* does not change the field current at all. This low temperature effect is therefore closely associated with the breakdown phenomena and it may be an indication of an effect of thoriation on field currents in contrast to the thoriation experiments described earlier in this paper.

Range of breakdown fields

The second breakdown illustrated in Fig. 6 occurred at about the same value of the average applied field as the first one. In general as a filament was repeatedly taken through breakdown, the required field increased in an irregular way to higher values. In Fig. 7 the range through which the breakdown fields progressed is shown for that particular thoriated tungsten filament.

Table II summarizes the range of fields (and the corresponding applied voltages) over which

TABLE II. *Breakdown fields for pure and thoriated tungsten filaments.*

Cathode Material	Cathode Diameter, mil	Field Range, v/cm	Voltage Range, kv
Thoriated Tungsten	1	$1.3–2.0\times10^6$	11.1–17.1
Thoriated Tungsten	1	$1.2–2.6\times10^6$	10.3–24.2
Pure Tungsten	1	$2.0–2.8\times10^6$	16.7–23.4
Pure Tungsten	0.6	$1.5–2.67\times10^6$	8.4–14.9

the breakdown progressed with two thoriated tungsten filaments and also two pure tungsten filaments. In all four cases the upper limit of the range was set by the filament separating during the breakdown. One must not necessarily infer that, had the filament remained intact, the breakdown would not have progressed to higher values.

This is probably particularly true of the two thoriated tungsten filaments since there was no indication that the field, at which breakdown was successively occurring, was approaching a steady value. On the other hand, prior to the breaking of the one-mil pure tungsten filament, approximately the same value of the applied field, 2.8×10^6 v/cm, gave many successive breakdowns. There is, therefore, some considerable justification for thinking that with this filament the maximum breakdown field has been reached. There was similar although less extensive evidence with the 0.6-mil tungsten filament that the maximum breakdown field had been approximately reached.

Factors controlling breakdown

1. *Degree of thoriation of cathode.* Tests were made with one of the thoriated filaments in which, by the proper heat treatment, different degrees of thoriation were obtained along with the accompanying value of the breakdown field. Table III summarizes those tests.

One readily sees that there is no significant difference between the value of the breakdown fields for the widely different degrees of thoriation. This result is not surprising in view of the experiments already described in which it was found that the field current characteristic curve was independent of the degree of thoriation of the filament.

TABLE III. *Breakdown fields for various degrees of thoriation of filaments.*

Test No.	f in %	Breakdown Field in v/cm
1	4	1.43×10^6
2	0	1.43
3	100	1.47
4	80	1.49
5	25	1.43
6	40	1.47
7	3	1.47
8	3	1.39
9	0	1.51
10	0	1.41

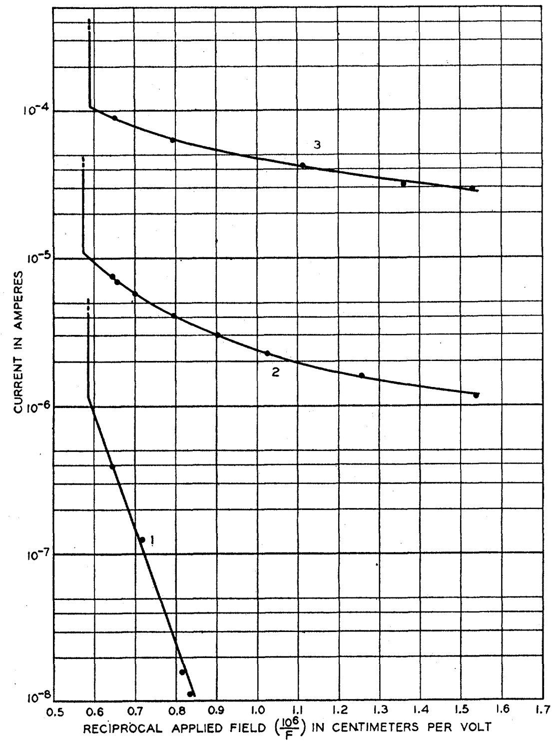

FIG. 9. Emission current *vs.* applied field data and the effect of filament temperature on breakdown. The vertical arrows indicate breakdown.

Curve 1 $T=300°K$
Curve 2 $T=1340°K$
Curve 3 $T=1670°K$.

2. *The temperature of the cathode.* If the onset of breakdown is determined at all by the energy dissipated in the tube or by the magnitude of the emission current then by raising the filament temperature, the resulting thermionic emission supplementing the field current by a large factor, one would expect the breakdown field to be decreased. Fig. 9 shows the results of such tests. With the filament successively at 300, 1340 and 1670°K, the breakdown fields were not different by a significant amount. Just before breakdown the current on curve 3 is about 300 times greater than the corresponding value on curve 1. Moreover at lower fields, the current is millions of times larger. Still the breakdown field is substantially unchanged.

This experiment shows that the energy dissipated in the anode or the emission current can be increased substantially without changing the breakdown field. This experiment however does not exclude the energy density dissipated on the anode or the emission current density from the filament as a factor in breakdown. A simple calculation shows that, if all of the field current comes from 1 percent of the surface and the thermionic current is uniformly emitted over the filament surface, then just before breakdown the current densities for curves 1 and 3 are about the same. Later on in this paper experiments are described which show that the emission of current is necessary to induce breakdown and that the anode probably is not a factor in the phenomenon.

3. *Can breakdown be induced by field alone? (Filament as anode.)* If breakdown occurs independent of an emitted current when the applied electric field reaches a certain value, perhaps because the mechanical force ruptures the filament surface, then one ought to observe the typical increase in field current following the usual breakdown if the usual breakdown field is applied *with the filament as anode.* The results of such a test are given in Fig. 10. Curves 1, 1′; 2, 2′; 3, 3′ were obtained with the filament as cathode and show the usual breakdown and effects thereof. In each of the three cases, the original low current curve was restored approximately by heating the filament. Next, with the filament as anode, a field of 1.59×10^6 v/cm was applied as indicated by the dashed vertical line in Fig. 10. This field was slightly in excess of those for the above three breakdown cases. The filament was again made the cathode and the data of curve 4 was taken. It agreed very well with the prebreakdown curves 1, 2, 3 rather than with those that followed breakdown. This shows that the electric field alone is not sufficient to produce breakdown but that an emission of current is necessary for the phenomenon.

4. *The suppression of breakdown by a high resistance in series with the anode.* Breakdown may be dependent upon the passage of the relatively large current of about 1.0×10^{-3} ampere at the breakdown field. This can be tested by using in the anode circuit a resistance of such magnitude that the voltage drop across it at 10^{-3} ampere greatly decreases the tube voltage. The results of such a test are shown in Fig. 11. With a resistance of 2.2×10^9 ohms, three excursions to $F=1.67\times10^6$ v/cm effected no increase whatever in the field current curve and there was of course no appearance of the characteristic large breakdown current. With a resistance of 1.0×10^8 ohms, the maximum field applied was $F=1.70\times10^6$ v/cm. Curve 4 resulted showing a relatively small but unmistakable increase over curves 1, 2 and 3. With a resistance of 1.0×10^5 ohms, which is the value used in the experiments already described, the field $F=1.70\times10^6$ v/cm resulted in the usual breakdown current and large increase in activity shown by curve 5. Subsequent measurements with this tube and a resistance of 1.0×10^5 ohms gave breakdown at $F=1.75$, 1.64, 1.70, 1.56×10^6 v/cm. All of the above values of breakdown fields are corrected for the voltage drop across these resistances. Hence it is felt that in the tests of Fig. 11 the absence of breakdown was not because the maximum field was too small.

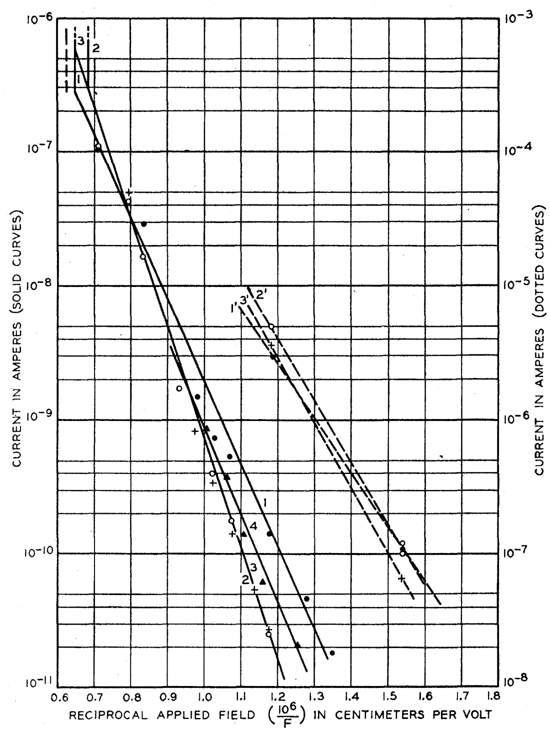

FIG. 10. Polarity of filament and breakdown. Curves 1, 1′, 2, 2′, 3, 3′ show usual breakdown. With filament as anode, $F=1.6\times10^6$ v/cm was applied after which curve 4 was obtained with filament as cathode.

Breakdown therefore can be suppressed by adding a sufficiently high resistance to the circuit, with this tube a resistance of about 2.2×10^9 ohms being sufficient. Other workers[11] investigating breakdown have observed much the same effect.

5. *Breakdown and the effect of the anode.* The tests so far described have been made with tubes in which the electrodes were in the form of concentric cylinders. The anode and exposed glass surfaces are possible factors influencing the breakdown. Tests on the effect of the anode on the breakdown are now described.

The experimental tube is shown in Fig. 12. The nickel anode is an accurately machined cylinder which is weighted on the inside so that it can be rotated by tipping the tube. One-third of the anode can thus be shielded from the discharge by the nickel shield shown. A definite curvature at the tip of the V-shaped 0.6-mil tungsten filament was obtained by shaping it around a 0.012-inch wire, applying tension, and flashing in hydrogen. The plan was to condition the tube with the portion A of the anode shielded until the tube would withstand breakdown at some voltage that was considerably higher than the first breakdown value. If a significant part of this conditioning process is a conditioning of the portion B of the anode, then by moving portion A to a position in front of the filament breakdown would occur at a value of the applied potential that is significantly lower than the highest value observed with portion B.

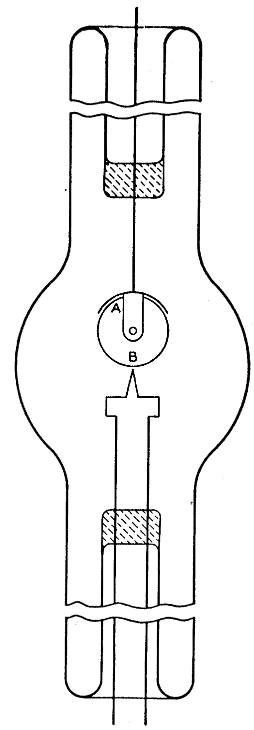

FIG. 12. Sketch of tube for investigating the effect of the anode on breakdown.

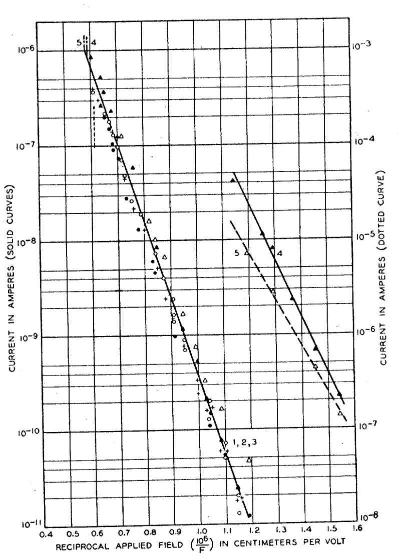

FIG. 11. Breakdown data and the effect of external resistance in anode circuit.

Curve	Resistance
1 (○), 2 (●), 3 (+)	2.2×10^9 ohms
4 (▲)	1.0×10^8 ohms
5 (△)	1.0×10^5 ohms

Maximum field (dashed vertical line) is 1.64×10^6 v/cm for curves 1, 2, 3.

In every case, with three different tubes, no effect on either the field current magnitude or the breakdown voltage was found when the portion A of the anode was placed in front of the filament. For example with one tube breakdowns were observed initially in the following order at 15.4, 22.0, 15.2, 16.0 kv. Then it was found that 19.2 kv could be applied without breakdown occurring. Then with the anode portion A next to the filament, breakdown did not occur until 21.8 kv was applied.

Therefore it appears to be quite definitely established that a tube which has been conditioned to withstand breakdown at a given voltage will not give breakdown at a significantly lower voltage when a portion of the anode, which has heretofore been shielded from the discharge, is exposed. Thus the anode would appear to be eliminated as a factor determining breakdown.

6. *Breakdown and the effect of exposed glass.* In the tests for an anode effect just described, the high degree of shielding of the filament and anode,

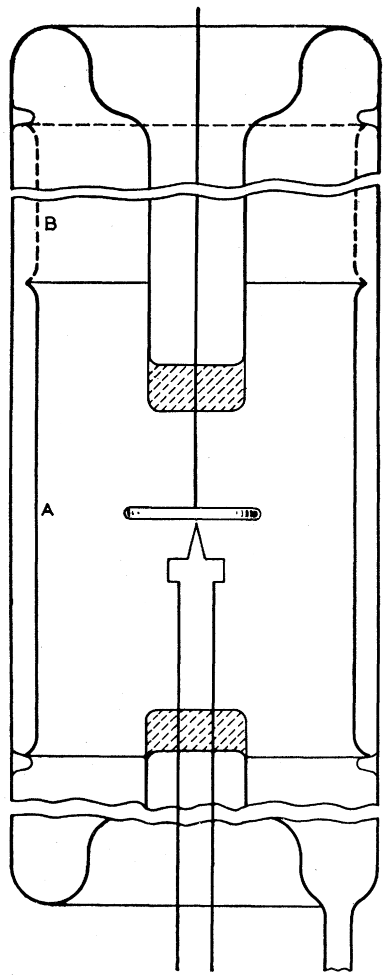

FIG. 13. Sketch of tube for investigating the effect of exposed glass on breakdown.

obtained with the concentric cylinder electrode arrangement, was dispensed with. In this case it is important to know how the exposed glass of the bulb may affect the breakdown phenomenon. This question is particularly pertinent with the tube of Fig. 12, since at breakdown much fluorescence appears on the glass.

This point was tested with a tube shown in Fig. 13. The anode consisted of a flat nickel disk. The tungsten filament assembly and electrode separation were the same as in Fig. 12. A glass sleeve was mounted inside the cylindrical glass envelope so that it could be at position A around the electrodes or at B away from them. The plan was to condition the tube with the glass sleeve at A until it would withstand breakdown at some voltage considerably higher than the initial breakdown value. If a significant part of this conditioning process is a conditioning of the glass sleeve then by moving it to B, thus exposing fresh glass, the voltage would be appreciably lowered.

The results of such an experiment are shown in Fig. 14. The first breakdown occurred at 16.2 kv and as shown after the sixteenth breakdown, the tube withstood 25 kv at which point the tube was removed from the pumps. Three more breakdowns then occurred as shown, after which the tube withstood 24 kv without breakdown. The glass sleeve was then moved to B and again several breakdowns occurred at potentials appreciably lower than 24 kv, the first one occurring at the same point as the initial breakdown with this tube.

Thus with this type of tube shown in Fig. 13 the condition of the exposed glass is a definite contributing factor in the breakdown. An examination of the concentric cylinder electrode tube used in the bulk of the experiments herein described will show that the filament and anode are very completely shielded from the glass of the tube. The data of Fig. 14 show that this shielding is necessary and important in breakdown studies of this sort.

7. *Unsuccessful attempts to produce breakdown.* An interesting case was encountered with one of the tubes of the type shown in Fig. 12. A number of breakdowns were observed which began at 15 kv and progressed up to 22.2 kv at which point the filament was separated by the breakdown discharge. After replacing the filament one break-

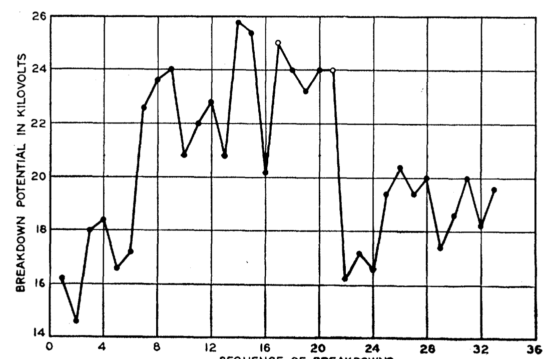

FIG. 14. Data on breakdown as affected by exposed glass. Fresh glass was exposed after breakdown No. 21.

down at 22.4 kv was observed after which the tube successfully withstood 25.4 kv.

The following attempts were then made to induce breakdown. *With the tube sealed off from the pumps*, the entire tube was heated to 500°C for about four minutes. Then with the tube at room temperature *breakdown did not occur* at 24.6 kv. Next the anode system was heated to a red heat for 40 minutes by high frequency induction. Again with the tube at room temperature the tube withstood 25.0 kv. The tube was opened up for three days, then pumped down, baked at 480°C, filament glowed, etc. *Again no breakdown occurred at 23.6 kv*. The diffusion pump was then stopped the pressure rising to 1×10^{-2} mm Hg for twenty-five minutes. Again, no breakdown occurred at 26.4 kv after the pressure had been reduced to about 1×10^{-6} mm Hg. The tube was then removed from the pumps and after standing at room temperature for several days, no breakdown occurred at 26.0 kv, but after standing for several days more a breakdown occurred at 26.4.

At one point in these tests the filament tip and anode were photographed with the voltage applied. From this the potential gradient form factor at the tip of the filament was calculated to be about 178. Thus with a potential of 26.4 kv, the average electric field of 4.7×10^{6} v/cm at the filament surface is *insufficient* to produce breakdown. This was the highest electric field ever observed to be insufficient to produce breakdown. Cases have been observed, with this type of tube, in which the tubes would withstand about 27 kv but because of a smaller form factor the average potential gradient at the filament was smaller than the above quoted value.

In the above tests no measure of the pressure was obtained when the tube was removed from the pumps. During the heat treatments the gas pressure undoubtedly increased considerably. Therefore there was much opportunity for gas contamination of the electrodes. These treatments do not appear to influence the occurrence of breakdown. They furnish no further information on the factors which do affect the phenomenon.

Breakdown with pure tungsten

In addition to the tests just described on the effect of the anode and exposed glass, breakdown experiments were made using pure tungsten filaments in tubes of the concentric cylinder electrode arrangement. In no way significantly different from the case of thoriated tungsten, breakdown occurred very abruptly after which it was found that the characteristic field current curve was raised to enormously higher currents. After breakdown, low temperature heating was not observed to increase the field current in contrast to the thoriated tungsten case already described. The characteristic curve can be reduced approximately to its original value simply by heating the filament to a high temperature in much the same way as with thoriated tungsten. In one respect, the breakdown phenomenon was unlike the thoriated tungsten case. The thermionic activity of the cathode remained unchanged by the breakdown. This proves that the increase in thermionic activity observed with thoriated tungsten is actually due to a thoriation of the filament by the breakdown and is not caused by contamination of the filament from some external source such as the anode.

Discussion

Experiments at the General Electric Laboratory[10] are briefly described in which electrical breakdown was observed. Abnormally large currents set in at a definite voltage and following this the characteristic curve at lower voltages was observed to be shifted to higher currents. These high currents were erased by cathode heating at or about 1600°K. With continued experimentation, the voltage required for breakdown gradually increased. Heating the anode, which was in the form of a filament, at 2500° while the bulb was in liquid air had no effect on the magnitude of the field currents.

Chambers[11] reported on breakdown studies with tungsten filaments which had received intense heat treatment. After 2800°K heat treatment a 0.5-mil tungsten filament gave breakdown at 11 kv whereas with a 1.6-mil filament it occurred at 23 kv. These voltages correspond to average fields of about 2.6×10^{6} v/cm and 2.0×10^{6} v/cm respectively. In addition, he found that with the 0.5-mil filament, immediately after heating the anode to a bright red heat for one

[10] Compton and Langmuir, Rev. Mod. Phys. **2**, April (1930).

[11] Chambers, J. Frank. Inst. **218**, No. 4, October (1934).

hour, breakdown did not occur at 25 kv but after several hours it again occurred at 11 kv. This and other tests were interpreted to mean that the breakdown is caused by positive ions which are emitted from the anode under electron bombardment and which in turn bombard the cathode surface.

Bennett[12] has reported breakdown studies in a series of papers. Many of his experiments were with electrodes of a form that could not be heated readily to high temperatures for outgassing purposes. Tests are reported with electrodes of different materials which were designed to show the effect of the anode and the effect of cathode bombardment on the breakdown. The experiments have been interpreted as showing that the anode has a large effect on breakdown. The results would appear to be confused by unknown effects introduced by exposed glass as described in his 1933 paper.

Probably the most important question regarding the electrical breakdown is the following: When breakdown occurs, is the determining factor the potential between anode and cathode or the applied field at the cathode? If breakdown occurs at a certain voltage it most likely is primarily an anode effect of some sort, but if it occurs at a certain value of the field it probably is primarily a cathode effect. Therefore probably the equivalent of the above question is as follows: Is breakdown caused by an effect originating at the anode such as the emission of positive ions from the anode and the cathode bombardment therewith; or is the breakdown caused by an effect originating at the cathode as, for example a rupture of the cathode surface by the electric field? The evidence from the present experiments although not conclusive indicates that the breakdown is determined primarily by conditions at the cathode. Some fairly direct evidence on this point is offered by the experiments summarized in Table II in which two different sizes of tungsten filaments were used. The maximum breakdown fields observed were about the same for the 0.6-mil filament and the 1.0-mil filament. However, the breakdown voltage for the larger filament was greater by about 60 percent. Of the four tubes listed in Table II, it should be noted that the initial breakdown voltage is lowest for the 0.6-mil filament although the corresponding value of the field is not thus distinguished. Although the evidence of Table II is not conclusive, it favors the thesis that breakdown is determined by the field at the cathode rather than by the applied voltage.

The experiment in which no effect on breakdown was observed when different parts of the anode were used is quite definite evidence that either the anode is not a factor in the breakdown or at least that the progression to higher fields is due to a conditioning of the cathode alone. Regardless of the mechanism by which exposed glass affects the breakdown as already described, this experiment indicates the importance of shielding the electrodes to eliminate the glass as a factor. In the concentric cylinder electrode tubes used in most of the experiments this shielding is very complete. It would be impossible for positive ions from the glass to reach the central portion of the filament. The electrostatic shielding of the electrodes against any "charging up" of the glass is very adequate. It seems very unlikely that neutral particles such as fine bits of glass would be deposited on a small central portion of the filament. It therefore seems reasonable that the effect of exposed glass as shown with the tube of Fig. 13 is adequately guarded against in the concentric cylinder electrode tubes. The experiments on the effect of the anode itself indicated no influence on the breakdown so that we have no direct evidence that the breakdown is not initiated at the cathode.

The test in which high fields were applied to the filament as anode show that breakdown cannot be produced by the electric field alone; an emission of electrons is necessary. The experiments in which the external circuit resistance was varied show that breakdown does not occur if the current that can pass is limited by such resistances.

When once it was experimentally observed that the field currents were independent of the degree of thoriation of a thoriated tungsten filament it was not surprising that the breakdown field was also independent of the degree of thoriation since an emission of field currents is necessary to obtain breakdown.

[12] Bennett, Phys. Rev. **37**, 582 (1931); **40**, 416 (1932); **44**, 859 (1933).

A proposed mechanism of the breakdown process

The electrical breakdown, which from the present experiments appears to be determined primarily by conditions at the cathode, might be tentatively pictured as follows: Before breakdown the field currents come from a few of the surface projections where the local applied field is greatest. Likewise the mechanical force associated with the electric field will be much greater at these projections. Depending on the size, geometry, etc., of these projections and their thermal contact with the body of the cathode, there will be a certain amount of local i^2r heating on the cathode. As the electric field is increased sufficiently, a rupture occurs on that projection where conditions of mechanical force, i^2r heating, and tensile strength are most favorable. When the rupture occurs, due to the greatly enhanced local field the large breakdown current passes and at lower fields much larger field currents are obtained. Heating the filament to a sufficiently high temperature after breakdown tends to smooth down and heal these ruptures thus reducing the local fields and currents as observed experimentally.

The next rupture and breakdown might occur again at the same projection. On the other hand succeeding breakdowns might occur at other projections at progressively higher fields in the order of their susceptibility to rupture.

Experimentally one observes that in general, repeated breakdowns occur at progressively higher fields. The experimental fact that a thoriated tungsten filament becomes partially activated by the breakdown is substantial evidence that at breakdown there is considerable local heating of the filament.

A similar picture of rupture and breakdown might be described wherein positive ions bombarding the cathode are the important factor. The breakdown experimentally observed might be a combination of both. An experiment, in which a transfer of anode material to the cathode could be detected, would give information on whether or not positive ions were bombarding the cathode. Such tests might be made with a tungsten filament cathode and a thorium filament anode.

If breakdown experiments with filaments, whose diameters were different by a factor of about 10, were made, the question of whether the field or the voltage is the determining factor could be quite convincingly settled.

Summary

1. Electron field currents from thoriated tungsten, with different degrees of thoriation, were found to be independent of temperature.

2. The characteristic field current curve was found to be independent of the degree of thoriation of a thoriated tungsten filament. It is not known whether this means that field currents are independent of the work function of the cathode or that the work function of the areas emitting field currents is unchanged during the thoriation cycles.

3. An electrical breakdown, a sudden discontinuity in characteristic field current curve, occurs with thoriated tungsten and pure tungsten cathodes.

4. This breakdown raises the field current curve to higher currents by an enormous factor. Current increases by factors from 10,000 to 10,000,000 were usually obtained.

5. With pure tungsten no change in the thermionic activity of the cathode results from the breakdown; with thoriated tungsten, the thermionic activity is increased showing that a partial thoriation of the filament has occurred.

6. Heat treatment at about 1300°K following breakdown generally further increases the field currents from thoriated tungsten but produces no such effect with pure tungsten.

7. The high field currents following breakdown can be erased by heating the cathode to about 2600°K for a couple of minutes.

8. The value of the applied field at which breakdown occurs is independent of the temperature and the degree of thoriation of a thoriated tungsten filament.

9. The emission of electron field currents is necessary for breakdown to occur. The application of an electric field of the usual magnitude with the filament as anode produces none of the usual effects of breakdown. Breakdown does not occur if a sufficiently high resistance is inserted in the circuit.

10. In general with successive breakdowns, the breakdown occurs at increasingly higher values of the applied field. None of this progressive

increase in the applied field at which successive breakdowns occur can be attributed to a conditioning of the anode. A definite part of this progressive increase in field can be attributed to conditioning of glass surfaces when they are exposed to the discharge.

11. A few tubes eventually would not give breakdown at about 26 kv which was the highest voltage available. Tests with one, in which there was opportunity for much gas contamination did not result in the subsequent occurrence of breakdown.

12. The highest electric field that could be applied to a cathode without breakdown occurring was about 4.7×10^6 v/cm.

13. The evidence favors the conclusion that the electric field applied to the cathode surface rather than the applied voltage is the more important factor in producing breakdown. The evidence likewise favors the conclusion that the anode has no effect on the breakdown and that when the shielding against glass surfaces is complete, the breakdown is determined primarily by conditions at the cathode.

14. The suggestion is made that breakdown involves a rupturing of the cathode surface under the action of local heating and mechanical strain associated with the electric field.

The author acknowledges with pleasure the continued interest of Dr. H. E. Mendenhall during the progress of the experiments and is indebted to Dr. J. A. Becker for many suggestions regarding the interpretation of the data and the form of the manuscript.

AUGUST 1, 1936 PHYSICAL REVIEW VOLUME 50

The Approximate Solution of Nuclear Three and Four Particle Eigenvalue Problems

EUGENE FEENBERG AND SIMON S. SHARE, *University of Wisconsin*

(Received May 23, 1936)

The problem of determining intranuclear forces from the mass defects of the hydrogen and helium isotopes is investigated under the assumption that the interaction potentials are proportional to a function $f(\alpha r^2)$ having the general form of a potential well and possessing the power series expansion

$$f(\alpha r^2)=1-\alpha r^2+c_1(\alpha r^2)^2/2!-c_2(\alpha r^2)^3/3!+\cdots$$

about the origin. With this assumption the Rayleigh-Schroedinger perturbation theory is applicable to the two, three and four particle eigenvalue problems. The perturbation calculation yields small corrections to the eigenvalues given by the "equivalent" two particle method. The corrections are checked very satisfactorily in a special case by means of a complicated variational calculation. Numerical results are given for two extreme forms of the neutron-proton model: Model I—Interaction between unlike particles only, Model II—Equal interactions between all pairs of particles. These results put close upper and lower bounds on the strength of the interaction between like particles in the model, intermediate between (I) and (II), which corresponds most closely to the experimental facts.

I. Introduction

The mass defects of the hydrogen and helium isotopes appear to require a nuclear model with strong attractive forces between neutrons and protons and somewhat weaker attractive forces between like particles.[1, 2, 3] However in the study of the eigenvalue problems it is convenient to consider two extreme forms of the neutron-proton model with

(I) Interactions between neutrons and protons only;

(II) Identical interactions between all pairs of particles.

The model which corresponds most closely to the experimental facts is intermediate between (I) and (II). If the eigenvalue problems associated with (I) and (II) are solved, the corresponding solutions for intermediate models can be obtained by a simple process of interpolation. The Hamiltonian operators for models (I) and (II)

[1] Feenberg and Knipp, Phys. Rev. **48**, 906 (1935).
[2] R. D. Present, Phys. Rev. **49** ,640 (1936).
[3] Massey and Mohr, Proc. Roy. Soc. **A152**, 693 (1935).