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SOME EXPERIMENTS ON THE BREAKDOWN OF HEATER-CATHODE INSULATION IN OXIDE-CATHODE RECEIVING VALVES

By G. H. METSON, M.C., Ph.D., M.Sc., B.Sc.(Eng.), Associate Member, E. F. RICKARD, B.Sc., and F. M. HEWLETT, B.Sc.

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SUMMARY

Sintered alumina used for the insulation of valve cathode heaters is preferentially liable to sudden failure in service when the heaters are at a positive potential with respect to the cathode. The phenomenon has been studied in conventional valves run in varying conditions and also, in more detail, on simple two-electrode systems using recrystallized alumina as the insulant.

The sudden failure is shown to be the last of three stages, (*a*) a time-consuming degradation of the insulant with rate exponentially related to operating temperature, (*b*) a period of intermittent sparking and arcing, and (*c*) a local weld between heater and cathode which appears as a more or less permanent circuit fault.

The initial stage is accompanied by a transfer of tungsten from the heater across the alumina, and it is this process which is strongly enhanced when the heater is the positive electrode. Production of positive tungsten ions under electron bombardment from the cathode is postulated, and it is shown that tungsten transfer and also insulation failure are greatly retarded when the alumina contains a pore-free layer. This may be achieved in the laboratory by surface fusion or by the use of monocrystalline sapphire.

Reasons for the apparent absence of widespread heater-cathode insulation failures are suggested.

(1) INTRODUCTION

(1.1) General Nature of the Insulation Breakdown

Cathode heaters normally consist of a fine tungsten wire formed in some suitable shape and covered with a thin layer of sintered alumina which insulates the heater from the interior of the nickel cathode core. For reasons of circuit design the heater and cathode core may be operated at different potentials, and a failure of insulation under this condition may give rise to circuit derangement.

Experience over the past few years seems to indicate that the probability of breakdown is related to the direction of the applied potential, and the dangerous direction is that of heater positive to cathode. When breakdown occurs it appears to be quite sudden, with a fall of insulation from a thousand megohms to a fraction of a megohm occurring in a time of less than a minute.

The paper describes the breakdown occurring in a range of common receiving valves, and records some preliminary experimental observations on the course and nature of the phenomenon.

(1.2) Scope of the Investigation

The investigation has been divided into two parts—a phenomenological inquiry into the breakdown of common receiving valves, and an experimental approach to the nature of the phenomenon through a simplified heater-cathode system.

(2) BATCH TESTS OF COMMON RECEIVING VALVES

(2.1) Testing Technique

The valve type selected for examination was a high-slope indirectly-heated pentode with a 2-watt cathode system. This particular type was adopted as it is in common use, it is made in the United Kingdom by all of the large valve manufacturers and it can be readily assembled in the laboratories at the Post Office Research Station. Test batches of a common type were therefore available from a wide range of manufacturing sources, and it was furthermore possible to vary the heater-insulant system over an experimental range in the batches assembled at the Research Station.

The general method of batch testing was to mount the test group on a substantial rack immune from mechanical shock and to run the group at some selected voltage with the heaters maintained at a positive potential of 36 volts over the cathode cores (this particular potential was selected as of interest to the Post Office in the operation of submarine repeaters). Breakdown of heater-cathode insulation was detected and recorded by automatic repetition searching over the valve bank, each position being tested at intervals not exceeding thirty minutes.

(2.2) Treatment of Data

(2.2.1) Distribution of Lifetimes within a Batch.

A study of the time to first failure of valves, within a batch tested in particular conditions, showed them to fall reasonably well into an exponential distribution with, consequently, a probability of failure constant with time. Results for one batch of 44 valves, shown graphically in Fig. 1, illustrate the extent of agreement between actual and theoretical distribution of survival for such an exponential distribution.

For an infinite population, the time-constant of the exponential may be determined at any stage as the sum of the lives of the failures and of the testing times of the survivors, divided by the number of failures. The corresponding calculation of average life of valves in a sample batch at any stage gives the time-constant for the population life-distribution curve within confidence limits which may be derived from the number of failures and the Poisson probability distribution.

(2.2.2) Batch Average Life.

The time-constant of the assumed exponential distribution curve, calculable within known confidence limits, may be taken as a measure of batch average life without the necessity for testing to failure the entire batch.

Calculated for 95% confidence limits, it has been used as the criterion for assessing batches of valves run in different conditions.

(2.3) Influence of Various Factors on Batch Average Life

(2.3.1) Heater Temperature.

Batches of valves were tested with different heater voltages. Heater temperatures were estimated from characteristics of heater current and voltage, using Shardlow's curves of resistance and temperature. The plot shown in Fig. 2 indicates a reasonably linear relationship between the logarithm of batch average life and the reciprocal of heater temperature. There was no indication that the nature of the breakdown had been altered at the

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The authors are at the Post Office Research Station.

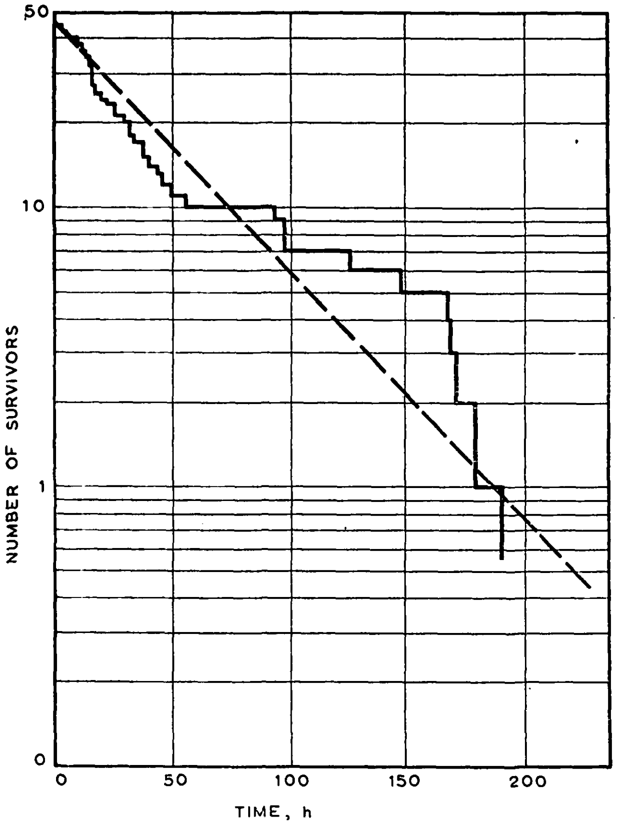

Fig. 1.—Distribution of survival within a batch of valves.
——— Curve showing actual survivors.
– – – – Theoretical curve.

higher temperatures, and many subsequent tests were accelerated by running the heaters with a 10-volt supply, giving a heater temperature of near 1 700° K.

(2.3.2) **Magnitude and Direction of Applied Direct Potential.**

All systematic testing has been carried out at the constant potential difference of 36 volts, but isolated tests at other potentials have left the impression that an increase in applied potential tends to shorten the average life.

Table 1

	No. of failures	Average life	Batch average life (95% confidence limits)
		hours	hours
Heater positive	46	50	38–68
Heater negative	10	6340	3 450–13 210

Evidence of a directional effect is given in Table 1 relating to two batches of valves tested at 1 700° K with a breakdown potential of 36 volts.

(2.3.3) **The Cathode Core and the Heater Metal.**

No evidence was obtained to show that life was affected by the use of platinum, nickel or molybdenum as the cathode core metal.

Also, no evidence was obtained to show that life was affected by the use of several varieties of silicated tungsten and molybdenum-tungsten as heater material.

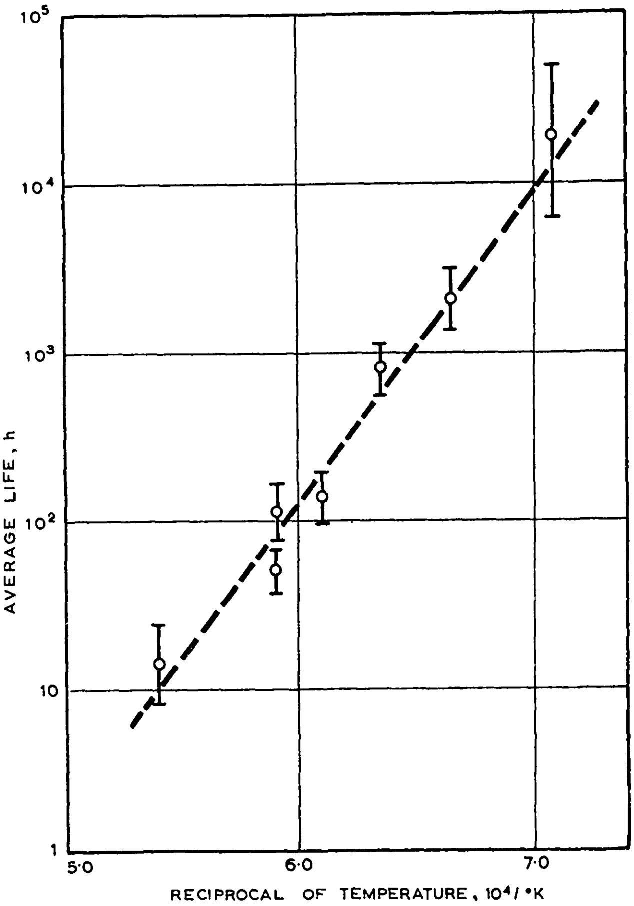

Fig. 2.—Batch average life as a function of temperature.
I 95% confidence limits for average life.

(2.3.4) **Heater Coating.**

Various commercial brands of alumina powder from English, American and German sources were made into spraying pastes and electrophoretic coating suspensions. Pastes used in the commercial coating of heaters were also tested. Heaters coated with these were sintered at different temperatures and mounted in valves. No marked variation in batch life was found, but there was an indication that some powders give slightly longer life when sintered in the range 1 650°–1 700° C in preference to temperatures above 1 700° C.

(2.3.5) **Heater Construction.**

One batch of valves had an unusually long life when tested with occasional inspection, but when the survivors were opened and examined, it was found that breakdown had occurred undetected. These heaters were of the "faggot" type, all others being folded spirals, and the apparent improvement in life was attributed to the facility of free movement of this type of heater. A repetition of the tests, under continuous inspection, gave a much shorter life.

(2.4) Breakdown Sites

(2.4.1) **Visual Appearance.**

After breakdown, heater coatings showed small stained patches the appearance of which suggested that they may have been due to arcing between heater and cathode. There was often a central dark spot with a metallic glint which lay at the bottom of a minute crater, and the inner surface of the cathode sleeve was roughened and stained in patches corresponding to the positions of the stains in the alumina. No connection could be established between visible physical imperfections in the original coating and the position of the stains, which were taken to be the breakdown sites. Fig. 3 shows part of a conventional heater after breakdown.

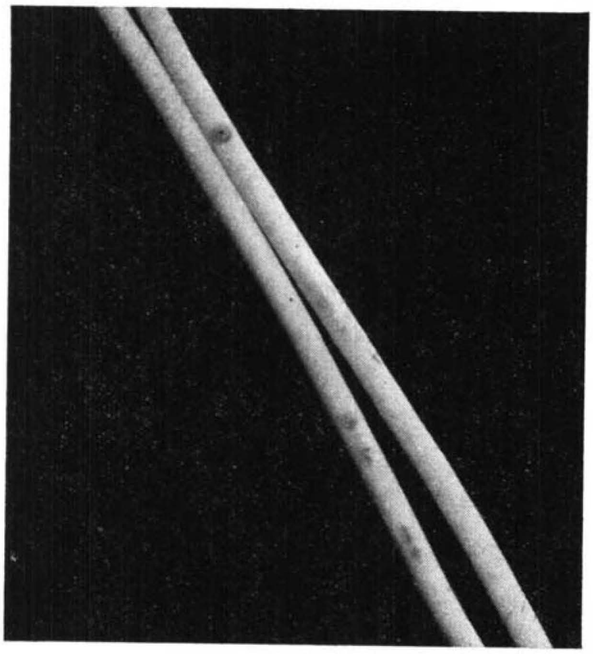

Fig. 3.—Conventional heater showing breakdown sites.

(2.4.2) **Stages of Growth.**

A survey of many scores of stains suggested that they had developed in a consistent sequence as follows:

Stage (*a*).—A small grey patch of indefinite shape.

Stage (*b*).—Enlargement and assumption of a well-defined, roughly circular shape of even grey.

Stage (*c*).—An intense stain at a central spot surrounded by an area of pale grey, bounded by a thin line of darker grey.

In a batch of valves run for constant time, the numbers of stage (*c*) stains on the heaters were roughly in the inverse ratio of the recorded times to first breakdown.

(2.4.3) **Chemical Tests.**

Chemical examination of material removed from stained portions of the heater showed tungsten present in all stains tested, and cathode core metal in some. There was always some staining material which could not be identified, being embedded in fused alumina grains, and this could have been heater or cathode metal or a compound of aluminium.

(2.5) Summary and Comments on Batch Tests

The results indicate that there is, in all the conventional heater-cathode assemblies tested, the liability of sudden breakdown of insulation. There is a marked directional effect, the liability being great when the heater is at positive potential with respect to cathode. This liability is an exponential function of operating temperature. The distribution of lives of valves within a batch approximates to an exponential distribution, which gives a constant probability of failure with time.

The nature of these batch test results can be correlated with the appearance and frequency of the breakdown sites if it is assumed that an initial time-consuming process leads to degradation of the insulant with consequent production of transient sparks or arcs which would not normally be detected by the intermittent testing mechanism. Movement of the heater would often prevent this appearing as a permanent fault, but the worst stains are seen when local adhesion has occurred. Such an event would cause the fault to remain until severe movement, e.g. the mechanical vibration of the whole valve, disturbed the contact. It was, in fact, found useless either to remove the valve or to reduce the temperature of the heater in attempts to measure the cold resistance of the path, since the local short-circuit generally disappeared.

(3) TESTS ON SIMPLIFIED SYSTEMS

(3.1) Technique

(3.1.1) **Description of Assembly.**

Commercial recrystallized alumina tubes, of bore 0·75 mm and wall thickness 0·43 mm, were cut to length so as to take a conventional 2-watt tungsten spiral heater, straight and uncoated. Around the exterior of the tube was wound in close contact a spiral of tungsten or platinum wire to serve as a second electrode. This assembly was mounted on a standard valve pinch, sealed in and pumped to high vacuum. Fig. 4 shows a typical assembly.

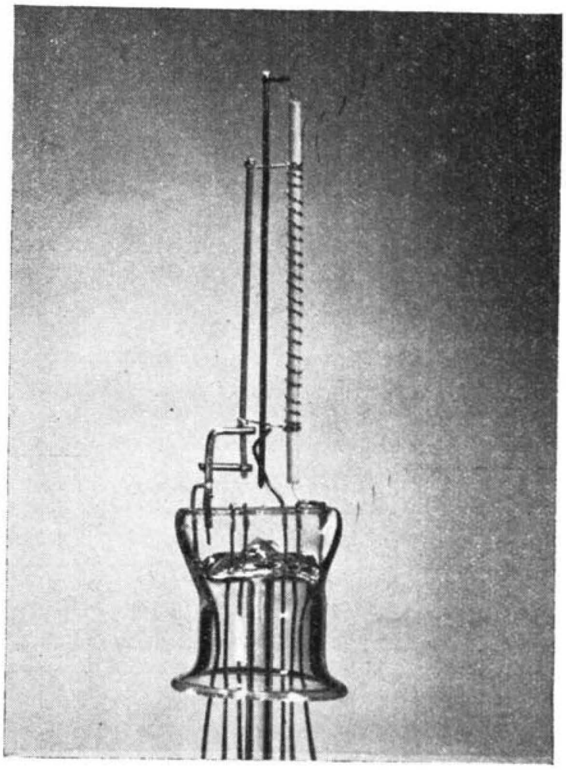

Fig. 4.—Simple assembly using recrystallized alumina tube.

(3.1.2) **Method of Test.**

Heater temperatures were adjusted by varying the voltage and were in general much higher than in the tests on normal valves—usually about 2 300° K. The surface temperature of the alumina tube was approximately 1 700° K measured by an optical pyrometer. The applied potential was 500 volts from a d.c. source, equivalent to a voltage gradient across the alumina of 10 kV/cm as compared with 5 kV/cm in the tests on normal valves. Leakage currents were measured by a suitable meter protected by a 0·5-megohm series resistor.

(3.2) Test Results

(3.2.1) Leakage-Current Characteristics.

The variation of current with time was studied, and a typical graph is shown in Fig. 5. An initial small rise was followed by a period of about 10 hours in which the current was stable. The current then rose rapidly, with violent fluctuation, to the value set by the limiting resistor, and this level was maintained for an ill-defined period terminated by heater burn-out. The curve of Fig. 5 has been smoothed to show the general trend in the rapidly rising period. During the initial stable period, it was possible to study the current/voltage relationship, and Fig. 6 shows this characteristic.

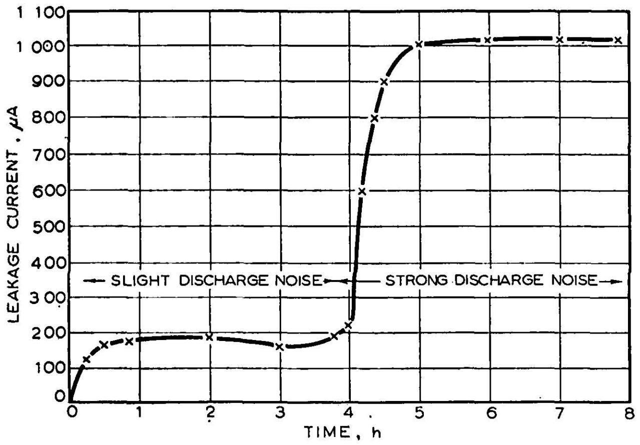

Fig. 5.—Current/time characteristic under breakdown-inducing conditions.

(3.2.2) Discharge Noise.

When a pair of high-impedance headphones was inserted in the d.c. circuit, it was noted that there was noise in the form of "clicks" superimposed on steady "frying." If the current was increased during the stable period by an increase in applied voltage, there was a rise in general noise level. During the unstable period, the rising current again produced a rise in background noise level and also resulted in increased frequency and loudness of "clicks."

(3.2.3) Breakdown Stains.

During breakdown, stains appeared on the outer surface of the alumina and developed roughly according to the scheme postulated in Section 2.4.2. These gradually grew together, producing a broad spiral band along the line of the external cathode wire. After breakdown, the alumina tube was sectioned and ground on Carborundum. Inspection of the stain shapes at different stages of grinding suggested that the stains had grown radially through the alumina from external cathode to internal anode (i.e. heater). Fig. 7 shows a typical stained tube and the same in cross-section.

(3.2.4) Effect of Reversed Potential.

Two tubes, both carrying tungsten heaters and tungsten spiral outer electrodes were run at the same temperature and applied potential. In the system where the inner, hot wire was positive, catastrophic breakdown occurred in about 10 hours. Where the outer, cooler wire was made positive no breakdown occurred in

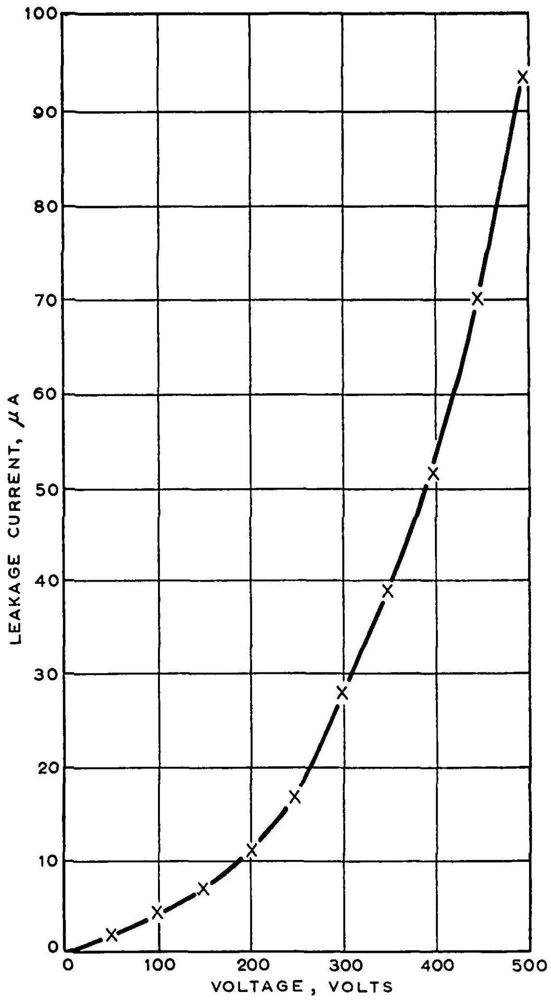

Fig. 6.—Current/voltage characteristic before breakdown.

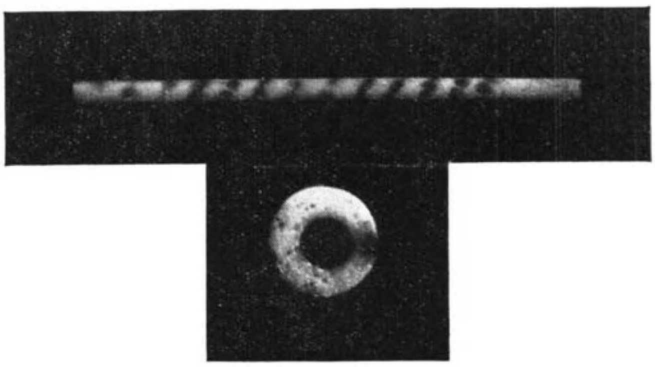

Fig. 7.—Tube and cross-section showing breakdown stains.

100 hours, and though there was some general discoloration of the alumina in the tube, there were no typical breakdown stains.

(3.2.5) Effect of Lowered Cathode Temperature.

Some assemblies were made in which the spiral cathode in close contact with the alumina was replaced by a hemicylinder of platinum foil separated from the alumina by a gap of about 1 mm. These were run with heater temperatures of 2350°K.

surface temperature of the alumina was approximately 1 800° K, but the temperature of the foil probably did not exceed 600° K. The potential was 500 volts, with heaters positive. After 300 hours there was no detectable leakage current and no stain formation.

(3.2.6) **Tungsten Transfer Phenomena.**

Fairly dense films of tungsten had often been found on the inner alumina surface of tubes and of normal heater coatings. In the tests described in Section 3.2.5 the bores were unusually clean, being practically free of tungsten despite the high temperature. A new test was made in which pairs of tungsten heaters were run at the same temperatures in the bores of small twin-bore alumina tubes with 500 volts applied potential between the heaters. One set was operated at 1 600° K and the other at 2 300° K. In each case the bore surrounding the positive heater was contaminated with considerably more tungsten than was present in the bore of the negative side. It is also of interest that the "bores" in the sapphire plate assemblies described in Section 3.3 were nearly free from tungsten film after 1 500 hours at 2 000° K. In those tests the cathode was hot, about 1 400° K, but passage of current was prevented by the nature of the insulant. These results suggest that bombardment of a heater by electrons from the cathode is probably a potent factor yielding enhanced tungsten transfer.

(3.2.7) **Effect of Fusing the Alumina.**

Some tubes were heated in an oxyacetylene flame until the outer surface was glazed, presumably giving a pore-free layer. One of these and an unglazed tube were tested under the usual conditions. The untreated tube suffered catastrophic breakdown in 8 hours, whereas the glazed tube maintained a steady insulation resistance of 5 megohms for over 300 hours. The stains in the unglazed tube were manifold and had in some places completely penetrated the alumina. The glazed tube showed only a few stains of negligible penetration. Fig. 8 shows this tube and it may be compared with Fig. 7.

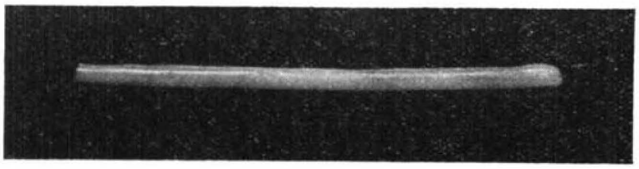

Fig. 8.—Surface-glazed tube showing slight staining.

(3.2.8) **Chemical Aspects.**

Tungsten emanating from the heater could always be detected in the stained portions of the tube, and in some instances it was also detected on a platinum outer electrode. When a platinum cathode was used, this metal also could be detected in the more intense stains. As with the ordinary heater coatings, there was present staining material within alumina grains which could not be identified.

(3.3) Use of Synthetic Sapphire

(3.3.1) **Description of Assembly.**

As an extension of the tests with glazed tubes, tests were made using monocrystalline alumina. Small plates of synthetic sapphire were grooved so that, when mounted in pairs, there was room for a conventional two-leg heater to lie in the grooves. The plates were bound tightly together with a spiral of platinum wire which served as cathode. The minimum wall thickness was 0·25 mm. The assemblies were run with the heater positive.

(3.3.2) **Test Results with Sapphire Plates.**

At first, the specimens were operated at heater temperature of 1 900° K and 500 volts from a d.c. supply. For 600 hours the insulation resistance remained greater than 10 000 megohms. The potential was then raised to 1 000 volts, equivalent to a maximum gradient in the alumina of 40 kV/cm, and the heater temperature was raised to 2 000° K. This was maintained for a further 1 500 hours during which no staining could be observed, and the insulation resistance remained greater than 5 000 megohms. The temperature was raised to 2 350° K, and after another 500 hours the heaters burnt out without any increase in leakage current.

(3.4) Comments on Tests with Simple Systems

These tests have given an insight into the nature of the processes occurring during the induction period. The chemical evidence suggests that transfer of tungsten into and across the alumina may be the rate-determining process during the induction period when gradual degradation of the insulant is thought to occur. The results with cool cathodes indicate that tungsten transfer itself is dependent on electron flow. The results with partly fused and monocrystalline alumina show that porosity is a necessary link between electron emission from the cathode and tungsten transfer into and across the alumina. They also show that ordinary electrolytic processes cannot play a major part in catastrophic breakdown.

(4) DISCUSSION OF RESULTS

The main results of these experiments may be summarized as follows:

(*a*) The breakdown, recognized in a working valve as a sudden failure of heater insulation, is the last stage in a process, the rate of which is an exponential function of temperature (Section 2.5).

(*b*) One feature of this process is the transfer of tungsten from the heater into and across the alumina (Section 3.2.8).

(*c*) Tungsten transfer is strongly dependent on the passage of current between cathode and heater (Section 3.2.6).

(*d*) The directional effect of applied potential observed in working valves is also observed in systems where both electrodes are of tungsten (Section 3.2.4).

(*e*) The leakage current and the transfer of tungsten are suppressed by the presence of a layer of non-porous alumina (Section 3.3.2).

An explanation of these facts can be given by assuming that positive tungsten ions are produced at the heater under electron bombardment. (These would move towards the cathode, and there is evidence that some tungsten actually reaches the cathode surface.) The rate of tungsten transfer is then dependent on rate of positive-ion production, and the latter depends on current magnitude and on the temperature of the positive electrode.

It is likely that some dissociation of the alumina itself, under electron bombardment, occurs simultaneously, and in this event oxygen ions will migrate towards the (anodic) heater and transfer of tungsten by migration as oxide is likely. The evidence does not permit a clear assessment of the importance of this stage.

The presence of tungsten in the alumina and of positive ions in the region of the cathode surface would both tend to an increase in local field-strength at certain points. Such an effect would be self-accelerating and would terminate in a breakdown arc, as is found to occur.

The breakdown can be avoided if the initial process, i.e. the bombardment of the heater with electrons, is prevented by interposition of a pore-free layer of alumina.

The mechanism outlined is undoubtedly simplified, but it probably includes the major factors responsible for heater insulation breakdown.

Having regard to the large number of series-operated a.c./d.c. receivers used on d.c. mains in this country with satisfactory results, it is curious that insulation breakdowns have not been more widely observed. In considering this point, the authors think it possible that the lack of widespread experience may be due to one or more of the following reasons.

(*a*) Electrical and mechanical life of the valve itself may in some cases be less than the insulation life of the heater.

(*b*) The breakdown "site" is unstable mechanically, and a low level of mechanical shock is usually sufficient to clear a fault. Examples have been found of valves with normal insulation but which have shown numerous breakdown sites when opened for examination. It is thought that such valves have suffered many heater insulation failures which have cleared themselves by mechanical shock derived, e.g., from normal handling or the thermal shock of heater voltage switching.

(*c*) A number of cases have been noted in which actual mechanical fracture of the tungsten heater wire has coincided physically with an insulation breakdown site. It seems reasonable to assume, therefore, that a proportion of heater open-circuit failures is due initially to the insulation breakdown phenomenon.

(5) ACKNOWLEDGMENT

Acknowledgment is made to the Engineer-in-Chief of the General Post Office for permission to make use of the information contained in the paper. The senior author also wishes to thank Mr. D. J. Ravenhill, who has been associated with the experimental work involved in the tests on simplified systems.

DISCUSSION ON "NOISE GENERATION IN CRYSTALS AND CERAMIC FORMS OF BARIUM TITANATE WHEN SUBJECTED TO ELECTRIC STRESS"*

Dr. R. Street (*communicated*): It has been shown by the author that the noise developed in ferro-electric crystals and ceramics can be ascribed to the occurrence of discontinuous changes in polarization, and the analogy to the Barkhausen effect in ferromagnetics has been pointed out. Attention has also been drawn to the time effects associated with noise generation by ferroelectrics. The similarity of the ferro-electric and magnetic cases may be even more striking than is claimed.

For ferromagnetic materials the change of the intensity of magnetization, consequent upon a stepwise change in the applied field, is time dependent.† The phenomenon has been termed magnetic viscosity or after-effect. It is generally accepted that the observed time dependence is due to the influence of thermal agitation on the domain processes. For example, under certain circumstances, thermal agitation may provide sufficient energy to activate the movement of a domain boundary from positions of metastable to stable equilibrium. The process is thus one of thermal activation of Barkhausen discontinuities. By making plausible assumptions it is possible to show that the time-dependent component of the intensity of magnetization should theoretically be of the form $I(t) = S \log t$.‡ The origin of time, t, is the instant at which the stepwise change in field is made. In simple cases, S is directly proportional to the absolute temperature and depends *inter alia* on the material of the specimen and on the point of measurement on the magnetization curve. The predicted form of $I(t)$ as a function of time has been observed experimentally for a number of materials, and, in particular, measurements of the quantity S have been made at different points on the magnetization curve. The maximum value of S for a given material occurs at, or near, the coercive force point of the magnetization curve. Thus the magnetic behaviour is similar to the ferro-electric behaviour illustrated in Fig. 11. Measurements on the temperature dependence of S, using specimens of Alnico and similar materials, demonstrated the linear relation predicted by theory. There are obvious difficulties in extending this to the ferro-electric case owing to the restriction of the available temperature range by the transition points and also by the increase in electric conductivity at the higher temperatures.

The majority of measurements on magnetic viscosity have been made by direct magnetometric measurement of the intensity of magnetization of the specimen. The slow response of the magnetometer makes it impossible to observe individual Barkhausen discontinuities while magnetic viscosity is proceeding. In the present connection it is interesting to note that the direct analogue of the ferro-electric method described by the author has been adopted in the investigation of magnetic viscosity of very-high-coercivity alloys.† In this form of apparatus the time differential of the intensity of magnetization is measured in terms of the e.m.f. induced in a search coil wound on a specimen placed between the poles of an electromagnet. For the majority of materials examined the e.m.f.'s induced by single Barkhausen discontinuities are not sufficiently large to be resolved as individual pulses; the observed e.m.f., V, is a smoothly decreasing function varying as $1/t$,

$$\text{for } V \propto \frac{d}{dt}[I(t)] \propto \frac{d}{dt}[\log t] \propto \frac{1}{t}$$

The failure to resolve the Barkhausen discontinuities is not surprising, since there is good evidence to show that for these specimens the volume of material involved in a Barkhausen discontinuity is about $10^{-17}\,\text{cm}^3$. However, with suitably heat-treated Alcomax specimens it is possible to observe directly the impulsive Barkhausen e.m.f.'s superimposed on a $1/t$ curve. The observed variation is essentially similar in form to that shown in Fig. 5.

It would be very interesting to know whether any results are available which could be used to demonstrate quantitatively the existence, or otherwise, of "ferro-electric viscosity." If the phenonemon does in fact exist there appears to be no major difficulty in applying the thermal activation theory, developed for magnetic viscosity, to the problem. This would be of value in that the results shown in Fig. 6 suggest that the processes involved may be of a particularly simple form. The movements of the domain walls are also directly visible as noted in Section 5.5.1. As is the case for observations on magnetic viscosity, it

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