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HIGH-POWER TRANSMITTING VALVES WITH THORIATED FILAMENTS FOR USE IN BROADCASTING

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SUMMARY

A major change that has occurred in high-power transmitting valves during the last decade is the introduction of the thoriated tungsten filament or cathode. The paper describes the technology of these cathodes and some of the valve characteristics resulting from the change-over from a pure tungsten cathode. Details are given of the various properties of thoriated tungsten cathodes resulting from the carburization process which is necessary to give stable emission. The performance is given of six typical types of transmitting valves used both in the sound and television services of the B.B.C. These are typical of many other types of large valves with thoriated cathodes which differ only in minor aspects from those described. Detailed performance results are given, together with a study of the economies of thoriated cathodes in practice. In considering the installation of these valves in place of the valves using bright tungsten cathodes, consideration has been given to the economic aspects of installation. Illustrations of the six types of valves described in the paper and survivor curves both for tungsten and thoriated tungsten valves are given, together with the curves showing loss of programme due to valve failure.

It seems clear from the results that not only do thoriated tungsten filaments or cathodes give economy in operation, but the lives in many cases are considerably extended.

(1) HISTORICAL NOTES

The discovery of the enhanced emission obtainable from tungsten filaments containing a trace of thoria was first made by Langmuir as early as 1914, but the first description of the phenomenon was not given by him until about 1923. Work in this connection had been carried out by several others towards the end of the First World War, and by 1922–23 several types of valve using a thoriated tungsten filament made their appearance. However, satisfactory valves were not produced until the process of carburizing the outer layer of the filament had been developed by heating it in a hydrocarbon vapour at about 2 300° K. This converts the outer skin of the filament to tungsten carbide, which is able to reduce the thoria in the operating range of temperature (1 900–2 100° K). The emission from a carburized filament is much more stable and less subject to vacuum conditions than an uncarburized filament, and is dealt with in more detail elsewhere in this paper. Some of the first small receiving valves, such as the DEQ and DEV, were produced with carburized thoriated filaments. These were followed fairly quickly by the LS5, which was a larger receiving valve and could, under suitable circumstances, be used as a transmitting valve dissipating up to about 10 watts at its anode at about 400 volts. This valve remained very popular for a number of years. Efforts were made to develop larger valves, and by the early 1930's valves capable of dissipating 250 watts at their anodes and by the late 1930's valves dissipating up to 1·25 kW with voltages of up to 3 kV became a practical proposition. It was soon apparent, however, that these valves had to be made particularly free from gas, because any ions present could bombard the filament and soon destroy its emission. The higher the anode voltage, of course, the more damaging did this effect become. At the commencement of the Second World War high-power valves were required for pulsed radar transmitters, and the cathodes had, of necessity, to have a large emission. Since the emission was required only for a fraction of the operating cycle, and for the majority of the time reactivation could take place, thoriated tungsten filaments proved very satisfactory, even with anode voltages of up to 40 kV. Valves for pulse operation were made both with silica and metal/glass envelopes and gave good lives. Large valves for continuous operation at high voltages could not be made until the development of continuously-acting getters, one of the most useful of which is zirconium. Since about 1948, large valves of 15 kW anode dissipation upwards have been made, operating with carburized thoriated tungsten filaments, and it is the purpose of the paper to survey the present situation and to give the results of the operation of these valves in practice, together with a study of the savings in operating power, particularly so far as filaments are concerned, compared with the more conventional type of large valve fitted with a pure tungsten filament.

The period since 1945 has also seen extensive development in radio transmission in the very-high-frequency field. Valves for this service require to be as small as possible in order to reduce inter-electrode capacitances and lead inductances, for which the thoriated tungsten filament is very advantageous. In fact, many of the most modern types of valves could not have been designed using a bright tungsten emitter. The development of these new types with thoriated tungsten filaments and the use of special grid material has led to many problems of mechanical design, some of which have become apparent only during the actual operation of valves in the field. There is no doubt that all these problems can be overcome in the course of time, and that all the new designs will be free from mechanical troubles and will run to the full emission life of the filament.

(2) TECHNOLOGY OF THORIATED TUNGSTEN FILAMENTS

(2.1) Reasons for Carburization

The addition of about 1% of thoria (ThO_2) to tungsten was originally made in order to modify the recrystallization properties of the metal. Langmuir[1] found that, by suitable heat treatment in vacuum, some of this thoria could be reduced to thorium which diffused to the surface, and the resultant surface monatomic film gave much enhanced thermionic-emission properties to the wire. This discovery led to the adoption of thoriated tungsten as a filamentary cathode, and a number of valve types

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were, in fact, successfully manufactured using the Langmuir process, both in this country and in America. At that time, however, it was not easy, with the techniques available, to obtain the degree of vacuum in the valves required to maintain stable emission.

Thoriated tungsten was really established as a commercially useful electron emitter only by the introduction of the carburizing process. This also appears to have arisen accidentally, in that carburization of lamp filaments, which occurred during processing in the residual pressure of oil vapour from the mechanical vacuum pumps, was being investigated at the same period. The fact that more stable emission was obtainable from carburized thoriated tungsten was observed by Langmuir and mentioned by him at the end of his first paper on the subject.

Concurrent work by Andrews[2] on the effects on emission of deposited films of thorium was misinterpreted to prove that the rate of evaporation of thorium from a carburized filament was lower than that from an uncarburized filament. This incorrect conclusion has been repeatedly quoted in subsequent literature as being a major factor in the improved emission stability given by carburization. In fact, a recent direct comparison[3] has shown that, at a given temperature, when the filaments are fully activated, the rates of evaporation of thorium from carburized and uncarburized filaments are equal, to the first order. The rates of supply of thorium to the surface layer from within the filament must therefore also be approximately equal, since there is no accumulation of thorium on the surface. A possible reason for the improved stability of emission of the carburized filament under imperfect vacuum conditions could be the break-up of the surface by the carburization. This gives more grain boundaries along which diffusion can take place, and therefore shorter migration distances across the surface to maintain uniform coverage.

During its life a carburized filament has the additional advantage that there is a continuous reaction between carbon and thoria at the operating temperature of 2000° K, thereby maintaining a sensibly constant supply of thorium in the filament. The uncarburized filament has to be flashed at 2800° K to promote reduction of thoria to thorium by the tungsten. Subsequent reduction at 2000° K is negligible, so that the usable reservoir of thorium built up during the flashing operation will steadily diminish throughout life.

(2.2) Methods of Carburization

The carburization of tungsten filaments may be carried out in a number of ways:

(*a*) By coating the surface with the required amount of carbon, and subsequently heating the coated wire in vacuum. The main difficulty in the application of this method lies in the sudden decrease of emissivity, and therefore rise of temperature, which occurs when the carbon in any area has been completely absorbed.

(*b*) By embedding the filament in bulk carbon and heating in a furnace. Partial carburization to a uniform depth in this manner is not easy.

(*c*) By electrical heating of the filament in the presence of a hydrocarbon gas or vapour.

Method (*c*) is the one usually employed. It may be carried out on the assembled valve during the pumping operation by the temporary introduction into the vacuum system of a solid with a low vapour pressure, such as naphthalene, or of a low pressure of a gas such as acetylene. It is more common, however, to precarburize, either as single filaments or as complete filament assemblies, in hydrocarbon vapour carried by hydrogen which has passed through a carburettor containing the liquid hydrocarbon, e.g. benzene, xylene, etc.[4] The filament temperature during this carburization is about 2300° K, and, owing to the cooling effect of the hydrogen, the heating power required is approximately four times the final running power *in vacuo*. The large powers involved make the use of water-cooled enclosures necessary. Carburization is not a critical procedure, the range of time and temperature to obtain a given result being fairly wide. The controlling factors are the rate of decomposition of hydrocarbon at the filament surface and the rate of diffusion of carbon into the tungsten. The rate of decomposition of hydrocarbon at the filament surface does not depend to any large extent on the temperature. Indeed, there is evidence that, when using naphthalene, every molecule reaching the hot surface is decomposed, so that the rate of decomposition depends only on pressure. When the hydrocarbon is in excess of hydrogen, this may not hold in detail, but filament temperature is still not a major factor. The rate of diffusion of carbon into the tungsten increases rapidly with rise of temperature. For any given partial pressure of hydrocarbon there is therefore a minimum temperature to use, below which carbon will build up on the filament surface, with consequent additional cooling by radiation, further drop in temperature and more deposition.

To carburize successfully, it is essential that water vapour and oxygen should be kept away from the hot filament. Thus condensation on the walls of the water-cooled enclosure must be avoided, constructional materials which give off water vapour when in contact with hot gases must not be used, and an adequate seal against the ingress of air must be provided. The degree of carburization used may depend on the wire size and on the valve in which it is used. As discussed in Section 2.4 the emission life is determined by the loss of carbon, so that a given fractional depth of carburization will give a longer life with a large-diameter wire than with a small one. Figures used commercially usually vary between 10 and 30% of the cross-sectional area, although Ayer[5] shows cross-sections of filaments with up to 40% of the area carburized. The process is usually carried out with the filament electrically heated at either constant voltage or constant current, and, in either case, the depth of carburization is controlled by the increase in filament resistance that occurs. The accuracy of this control will depend on the maintenance of uniform surface finish—and therefore uniform radiating properties—on the wire used. In one method of manufacture, a greater cross-sectional area is carburized than is finally required, and the heating is then continued for a short time in pure hydrogen to decarburize a shallow surface layer. A photomicrograph of the cross-section of such a filament is shown in Fig. 1.

(2.3) Effects of Carburization on the Properties of Tungsten Filaments

(2.3.1) Composition.

The changes in chemical composition of tungsten filaments which occur during gaseous carburization have been described by Horsting.[4] The phase diagram deduced from his and earlier work, which has been slightly modified by Norton,[6] shows that the part of the metal which is usually referred to as uncarburized is, in fact, a solution of about 0·05% of carbon in tungsten. The carburized layer formed under the correct conditions, i.e. without surface deposition of carbon, consists of di-tungsten carbide (W_2C) which has some tungsten dissolved in it. The existence of this definite phase gives rise to the sharp demarcation line as the diffusion goes inward. The solubility of tungsten in di-tungsten carbide becomes less as the temperature is lowered, and some therefore precipitates on cooling. This gives rise to a characteristic laminar structure which often shows in cross-sections of cold filaments (Fig. 1).

The specific gravity of di-tungsten carbide is less than that of tungsten, so that the process of carburization will increase the volume of a filament, and therefore its diameter. The specific

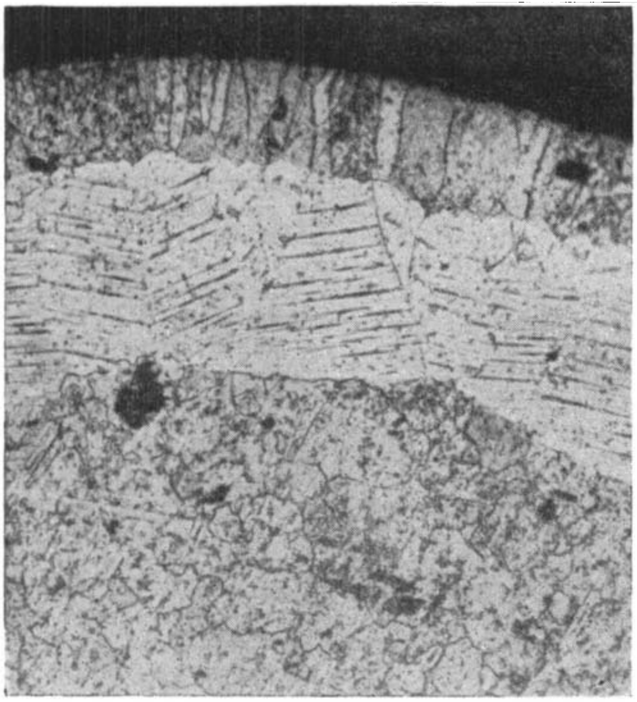

Fig. 1.—Photomicrograph of filament section showing decarburized surface.

gravity of the metals,[7] especially when thoriated, depends to some extent on the details of manufacture and processing, but taking figures of 19·0 for thoriated tungsten and 17·0 for thoriated tungsten carbide, a filament after carburization of 25% of its cross-sectional area will increase in volume by 3%, or, if this increase is all assumed to take place radially, will increase in diameter by 1·5%. This increase can, under some conditions, form a useful indication as to whether wires have been carburized.

(2.3.2) **Thermal Properties.**

The thermal expansions of di-tungsten carbide and tungsten are given in the literature as follows:

Tungsten carbide[8] (20–2400° C): $1\cdot 2 \times 10^{-6}$ per deg C, in the *a*-axis direction.
$11\cdot 4 \times 10^{-6}$ per deg C, in the *c*-axis direction.
Tungsten[9] (at 20° C): $4\cdot 5 \times 10^{-6}$ per deg C.
(20–2400° C): $5\cdot 8 \times 10^{-6}$ per deg C.

The large amount of anisotropy in the carbide crystals and the difference between the mean expansion of the carbide and that of tungsten will lead to the development of internal stresses in the wire on temperature cycling, and, if there is any tendency to split in the original wire, these will probably open up (Fig. 2) as a result of carburization.

The thermal emissivity of filaments with a tungsten-carbide surface is 20% higher than that for uncarburized tungsten filaments.

The melting point of the eutectic between tungsten and di-tungsten carbide is 2750° K, compared with 3680° K for pure tungsten and 3130° K for di-tungsten carbide. This lower melting point is, however, still far above the usual operating temperature range of thoriated tungsten filaments (1950–2050° K).

(2.3.3) **Mechanical Strength.**

Although no precise data on the bending strength of carburized wires are available, general experience indicates that they are more brittle than similar uncarburized wires. They are, however, adequately strong for use in large transmitting valves, where protective measures for transit must be taken in any case. The brittleness decreases rapidly with rise of temperature and is negligible at a few hundred degrees Celsius.

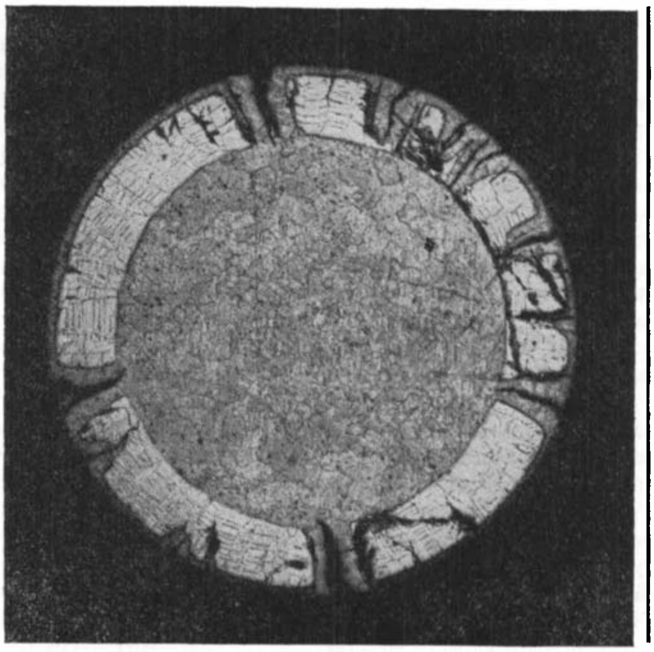

Fig. 2.—Photomicrograph of split wire.

(2.3.4) **Electrical Resistance.**

The resistivity[6] of di-tungsten carbide is 80×10^{-6} ohm-cm at 293° K and 119×10^{-6} ohm-cm at 2000° K, while that of tungsten[10] is $5\cdot 5 \times 10^{-6}$ ohm-cm at 293° K and $55\cdot 7 \times 10^{-6}$ ohm-cm at 2000° K. From these figures the increase in resistance of a wire as a function of the percentage of the original cross-sectional area which has been carburized may be determined. Thus if 25% of the original area is carburized, the hot resistance will increase by 15%, and the cold resistance by 30%.

(2.3.5) **Electron Emission.**

Carburization has no measurable effect on the magnitude of the electron emission obtainable from thoriated tungsten at a given temperature.[7] It does, however, markedly affect the ease with which the emission is obtained. The high-temperature flash at 2800° K described by Langmuir is no longer necessary; it would, in fact, be harmful, since it is above the melting point of the tungsten–tungsten-carbide eutectic. Normally the slight over-voltage the filament receives during the pumping operation is quite adequate for the carbon to reduce sufficient thoria to obtain the required monolayer of thorium on the wire surface, and therefore the emission. The saturated emission obtainable is of the order of 3–4 amp/cm^2 at 2000° K, with an emission efficiency of 100–120 mA/watt.

(2.4) Effects during Life

(2.4.1) **Loss of Emission.**

The emission from thoriated tungsten depends on the maintenance of a monatomic film of thorium on the surface. This thorium arises from the reduction of thoria by carbon, and the loss of emission which occurs at the end of life could therefore be due to loss of either thoria or carbon. All experience with glass-envelope valves indicates that it is the carbon which is lost first, adequate thoria still being present in the filament. Experience with large cooled-anode valves shows that their emission lives are longer than those obtained from glass-envelope valves, but that, unless the life is about 100 000 hours or more, it will probably still be terminated by the loss of carbon.

(2.4.2) Loss of Carbon.

With tungsten containing 1% of thoria, the amount of carbon necessary to give complete reduction of the thoria would be obtained by converting a little above 3% of the cross-sectional area to di-tungsten carbide. As it is usual to carburize between 10 and 30% of the cross-sectional area, the majority of the carbon must be lost at the surface by evaporation or chemical reaction with residual gases. Figures for this rate of loss have been given by Ayer,[5] and are plotted in Fig. 3 for comparison with data obtained by Wright[11] under controlled conditions, and with the rate of evaporation of carbon from bulk carbon.

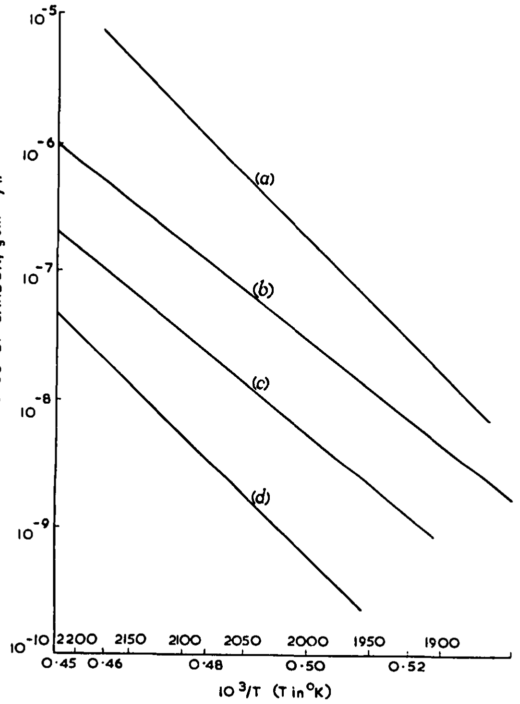

Fig. 3.—Loss of carbon as function of temperature.

(a) Ayer.
(b) Wright (10^{-5} mm H_2O).
(c) Wright (10^{-6} mm H_2O).
(d) Carbon.

Ayer's figures, which were obtained from operational experience with glass-envelope valves, almost certainly underestimate the life that can be obtained from modern cooled-anode valves, where the vacuum conditions are better. The figures indicate that a 1 mm filament, with 25% of its original cross-section carburized, would lose all its carbon in about 35 000 hours when run at 2 000°K.

Wright's figures refer to conditions without anode current flow, and therefore without positive-ion bombardment of the emitting surface. They may therefore underestimate the rate of decarburization for given vacuum conditions. It is known in practice that a shorter emission life is obtained when a given type of valve is run at a higher mean cathode current. True figures for the mean life, as determined by carbon loss, must therefore await further operational experience.

The location as well as the amount of tungsten carbide in the filament will change during life, since both are dependent on the rate of loss of carbon and on the rate of its diffusion through the metal. Previous published work has usually dealt with cases where the emission life was relatively short. In these cases the rate of carbon loss had the greatest effect, and, in much the same way as in surface decarburization during processing (Fig. 1), the carbon disappeared mainly from the outer surface of the original carbide layer.

For the long-life high-power valves, where the rate of loss of carbon is low, the picture is quite different. The diffusion process is now predominant, and it is found that a distribution of carbide particles is produced which is roughly uniform across the section of the wire. The photomicrograph of Fig. 4 shows this for a filament from a valve which still had good emission after running for 7 000 hours. In this case the inward diffusion has not gone to completion, the concentration of carbide in the originally carburized layer still being considerable.

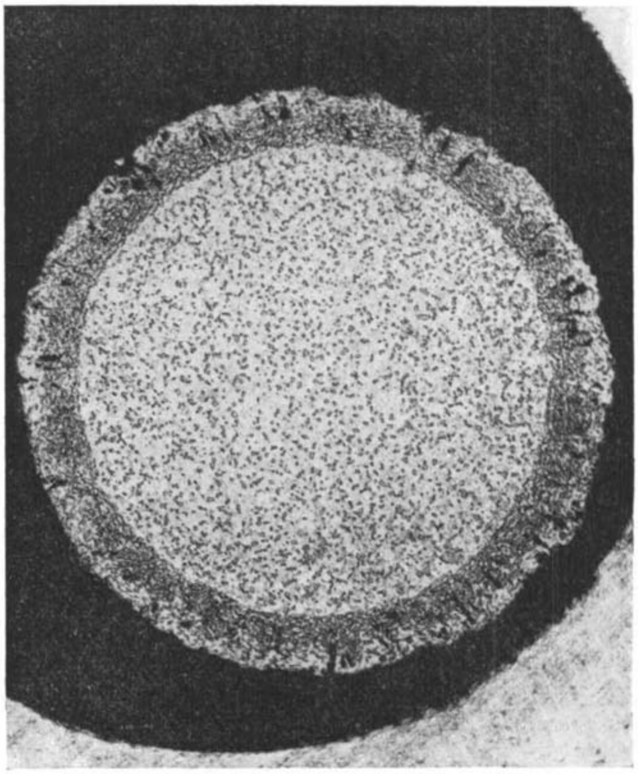

Fig. 4.—Photomicrograph of filament showing carbide disseminated as particles over cross-section of wire.

The change in electrical resistance of the filament during life will be affected by the pattern of the tungsten-carbide location. If the carbide has a tubular section, occupying a fraction, p, of the total volume, then, neglecting the effects of the change in volume on carburization, the effective conductivity, σ_1, of the composite metal will be given in terms of σ_w, the conductivity of tungsten, and σ_c, the conductivity of tungsten carbide, by

$$\sigma_1 = \sigma_w - p(\sigma_w - \sigma_c) \quad . \quad . \quad . \quad . \quad (1)$$

Where $p = 0{\cdot}25$ initially and the carbide section remains tubular through life with loss of carbon at a uniform rate, the change in effective room-temperature conductivity with time will be linear as shown by Fig. 5 [curve (*a*)].

However, if the carbide becomes uniformly disseminated as small particles through the tungsten, the effective conductivity, σ_2, will be given by[12]

$$\sigma_2 = \frac{2\sigma_w + \sigma_c - 2p(\sigma_w - \sigma_c)}{2\sigma_w + \sigma_c + p(\sigma_w - \sigma_c)}\sigma_w \quad . \quad . \quad . \quad (2)$$

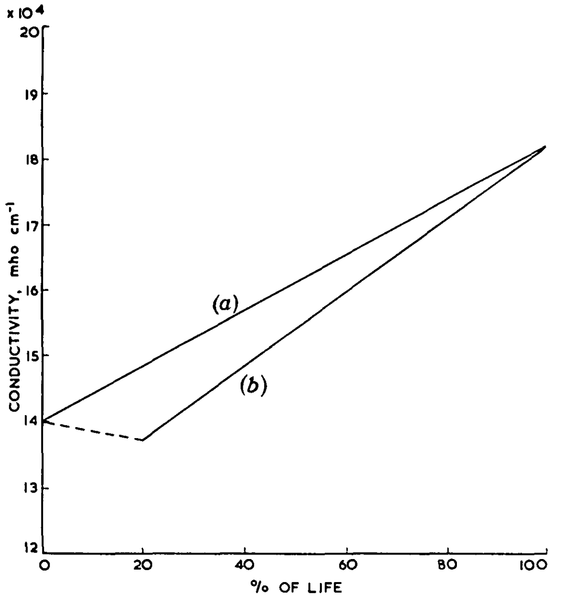

Fig. 5.—Change of effective conductivity during life.
(a) Tubular carbide section. (b) Disseminated carbide.

For $p = 0{\cdot}25$ initially, and the change to uniform dissemination taking place in the first 20% of the life, the effective conductivity during life is given by Fig. 5, curve (b).

These curves show that, without knowledge of the disposition of the carbide in the filament, it is not possible to use resistance measurements made during early life to determine the rate of loss of carbon, and therefore to predict the probable ultimate emission life of a valve.

(2.4.3) **Loss of Thoria.**

The work of Jenkins and Trodden[3] shows that, at a running temperature of 2000° K, the rate of loss of thorium from a carburized filament is about 7×10^{-12} g-cm^{-2}/sec. If this is assumed to remain constant throughout life, then, for a 1 mm filament, the time for complete loss of the original 1% of thoria will be about 150000 hours.

(2.5) Effects of Thoriated Tungsten Cathodes on the Properties of Valves

(2.5.1) **Filament Characteristics.**

The rate of change at operating temperature of many parameters of pure tungsten filaments for small changes of voltage or current is well known (see, for example, Reference 13). The corresponding approximate figures for the free-space characteristics of carburized thoriated tungsten at 2000° K are as follows: A 3% increase in applied voltage produces 2% increase in current, 5% increase in power, 1% increase in temperature, 20% increase in emission, and 50% decrease in life due to carbon loss. In practice, some of these figures may be modified a little by heat reflection from surrounding electrodes and by the cooling effects of filament supports.

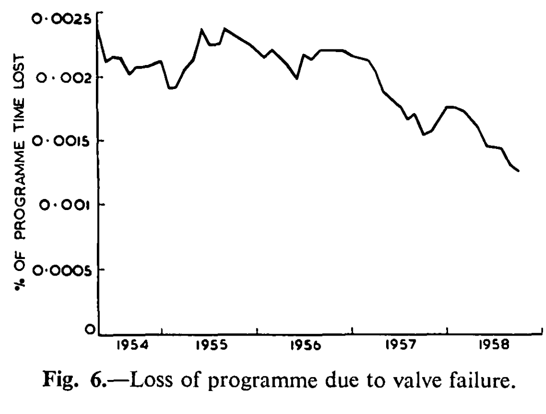

Fig. 6.—Loss of programme due to valve failure.

(2.5.2) **Grid Emission.**

When using pure tungsten filaments, the major limitation to the power output from a given size of valve is the cathode emission, and the rest of the structure is designed to suit this. With thoriated tungsten filaments, however, the distillation of thorium on to the grid surfaces reduces their work function so much that primary grid emission often becomes the limiting factor in design.

In valves with pure tungsten filaments, the internal metal surfaces may be made very clean and reproducible during the processing, and primary grid emission can occur only at very high temperatures. For example, for tungsten and molybdenum, the most commonly used grid materials, the temperatures required to give an emission of 1 μA/cm^2 are about 1600° K and 1500° K, respectively. When these metal surfaces are covered with thorium, it is possible to obtain the same emission at about 1100° K.

In practice, some grid emission can be tolerated in a large transmitting valve. However, owing to the combined effects of radiation from the filament and direct electron bombardment, the grid may have to operate at a temperature where emission from tungsten or molybdenum would become excessive, and some suitable treatment of the grid surface must be used to reduce the emission. A common treatment is to use a sheath of platinum applied during wire manufacture, while coatings of zirconium or titanium or their compounds are also used. In these ways the temperature for a given grid emission can be raised by at least 300° K.[13]

(2.5.3) **Anode and Grid Currents.**

The thoriated-tungsten transmitting valve is always operated with a peak cathode current several times less than the saturated cathode emission. The result is that the effect of saturation on the valve characteristics is negligible, and in this respect is different from the tungsten-filament valve. The latter valve commonly shows saturation from some parts of the filament at a total current well below the overall saturation level. As a result, characteristics of tungsten-filament valves cannot be deduced from a few parameters, such as amplification factor, mutual conductance, etc. On the other hand, the characteristics of valves with thoriated tungsten filaments follow simple theoretical considerations much more closely, and the characteristics can be deduced from basic parameters to a useful extent. Provided that the space-charge law is obeyed, which it will be so long as no part of the cathode is saturated, the cathode current of a triode valve is related to the voltages on the anode and grid by the formula

$$I_k = \mathscr{P}(V_g + V_a/\mu)^{3/2} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where $\mathscr{P}$, the perveance, and $\mu = \partial V_a/\partial V_g$, the amplification factor, are basic constants of the triode and are independent of the voltage and current. The constant μ is familiar to all valve users. For triodes its value lies in the range 5–100. The constant $\mathscr{P}$, although basic and often quoted for the electron guns used in beam devices such as klystrons, may not be familiar to some users. It is usually given in micropervs (1 perv = 1 amp/volt$^{3/2}$), and a typical figure for a 20 kW triode would be in the region of 1000 μp.

It has been customary to specify triodes by the values of the amplification factor, μ, and the mutual conductance, $g_m = (\partial I_a/\partial V_g)$, although the latter is far from constant and may, in some parts of the operating range, differ by a factor of at least two from the manufacturer's quoted value. In the negative grid region none of the cathode current will go to the grid, and g_m may be obtained by differentiating eqn. (3) to give

$$g_m = \tfrac{3}{2}\mathscr{P}^{2/3}I_a^{1/3} \quad . \; . \; . \; . \; . \; . \quad (4)$$

which shows how g_m varies with anode current when $\mathscr{P}$ remains constant.

In the positive grid region some of the cathode current is intercepted by the grid and is lost to the anode. The division of current between anode and grid may be defined by a third constant, the current division ratio, δ, given by

$$\delta = \left(\frac{I_a}{I_g}\right)_{V_a = V_g} \quad . \; . \; . \; . \; . \quad (5)$$

which is not dependent upon the absolute values of V_a and V_g. When V_a is greater than V_g the division ratio over the range $V_g < V_a < 4V_g$ may be estimated from

$$\frac{I_a}{I_g} = \delta\left(\frac{V_a}{V_g}\right)^{1/2} \quad . \; . \; . \; . \; . \; . \quad (6)$$

which applies over those regions of the characteristics where the major part of the grid current arises.

It will usually be found that direct substitution of thoriated tungsten for pure tungsten in a given valve design will, if anything, increase the ratio of grid current to anode current for given grid and anode voltages. However, the lack of saturation will normally mean that the required anode current can be obtained with less positive grid drive, so that less drive power will be required for a given maximum output power.

One other more subtle difference is shown in the grid-current characteristics. The grid current for small positive grid voltages rarely becomes negative, as it often does with pure tungsten filaments. This is because the thoriated tungsten filament has more emission from its cold ends, and the space charge from this prevents the escape of secondary electrons from the grid to the anode.

(2.5.4) Switching Transients.

The cold resistance of a carburized thoriated tungsten filament is about one-eighth of its hot resistance. When switched in the cold state on to a low-impedance supply, heavy currents will flow and the magnetic forces between filament limbs may cause distortion. This is a known problem with pure tungsten filaments, and is dealt with by multi-step switching using series resistances, or other suitable means of current limiting. For a given diameter of filament, the combined effect of lower running current and of the lower ratio of hot to cold resistance gives a surge current with carburized thoriated tungsten which is only about 40% of that obtained with pure tungsten, and is therefore dealt with more easily. With a.c. supplies a current-limiting transformer may be used. If a switched series resistance is used, this may conveniently be a single resistance whose value is 70% of the hot filament resistance and which is short-circuited after 20 sec.

(2.5.5) Hum.

When directly heated filaments are operated on alternating current, the anode current is modulated both by the electric and magnetic fields of the filament. The magnetic component is proportional to the square of the filament current per limb.

For a given geometrical design of filament and a given working anode current, the increased emission per unit area obtained by changing from tungsten to thoriated tungsten would enable the filament diameter and therefore the current per limb to be reduced. For other reasons, usually that of mechanical strength, this diameter reduction is not always incorporated. However, the lower operating temperature will still give lower current for the thoriated tungsten filament, and, in practice, the hum level is usually reduced by about 4–5 dB by the change from pure tungsten.

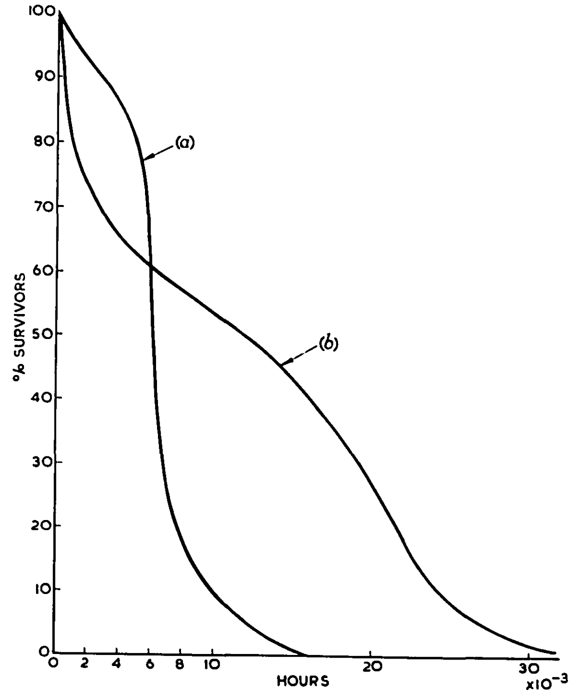

Fig. 7.—Survivor curves for (*a*) bright tungsten and (*b*) thoriated tungsten filament valves.

(2.5.6) Circuit Currents.

Theoretical considerations indicate that the r.f. currents flowing through the thoriated filament in a valve could have a marked effect on its life if the valve is loaded to the full extent allowed by the emission. As an example, consider a particular tetrode with a grid-cathode capacitance of 50 pF, of which approximately half is active capacitance, operating at a frequency of 200 Mc/s, with a 400-volt r.m.s. swing applied to the input. Under these conditions the r.m.s. capacitive current flowing between grid and cathode will be 25 amp and the r.m.s. space current will be about 6 amp. Because of skin effect, the combined action of these r.f. currents, acting in addition to the 175 amp heating current, will be to raise the temperature of the filament system at one end by about 50° C. Since the rate of evaporation of carbon changes by about 2% per deg C at the operating temperature, the presence of the r.f. current should appreciably affect the life. There is some evidence that this can be detected in valves used in the broadcasting service at frequencies greater than 100 Mc/s.

(3) HIGH-POWER TRANSMITTING VALVES IN USE IN THE B.B.C. SERVICE

High-power transmitting valves were last fully surveyed before The Institution in 1938 by Bell, Davies and Gossling.[15] While the general principles of construction have remained the same, many modifications and improvements have been made, particularly in improving the robustness of the valves, and in designing them for

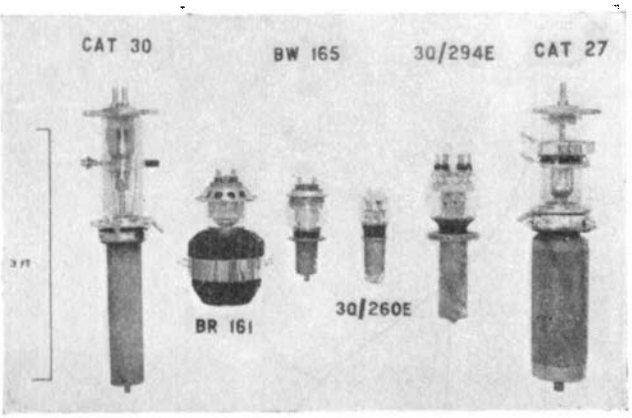

Fig. 8.—Illustrations of six types of thoriated-filament transmitting valves.

use at much higher frequencies. Fig. 8 shows six types of large transmitting valves using thoriated tungsten filaments which are in use in the B.B.C. service. A number of other types of large thoriated-filament valves are also in use, and although the following Sections are confined to the six types of Fig. 8, for which the maximum information is available, the authors have every reason to believe that the others will give comparable results in practice.

(3.1) General Description of Six Types of Large Transmitting Valves in Use at Present in the B.B.C. Service

(3.1.1) CAT27 and 3Q/294E.

The CAT27 and 3Q/294E are considered together as they have both been used by the B.B.C. as substitutes for the bright-tungsten-filament CAT17C valve which has been used for many years in double-ended transmitters operating class-C anode-modulated radio frequency up to 26 Mc/s. They are very different in size and a comparison of their performance is of considerable interest. The CAT17C has a filament power of 14·7 kW (32 volts at 460 amp) and the two substitute valves are shown in the following Table, which also gives the physical dimensions:

	P_f kW	V_f volts	I_f amp	Weight lb	Overall length in
CAT27	5·0	17·5	285	76	44½
3Q/294E	2·5	12·5	197	23	26½

The CAT27 was designed to be physically interchangeable with the CAT17C. The 3Q/294E, on the other hand, takes full advantage of the higher cathode efficiency of thoriated tungsten filaments to achieve smaller physical dimensions. This valve is in use in transmitters in many parts of the world, and its small size is of considerable importance in transportation. It will be seen that the change-over involves considerable differences in first cost, the CAT27 requiring only a change in filament voltage, whereas the 3Q/294E involves major changes, principally to the water jacket. The increased cost of change-over is just about equal to the difference in first cost of the respective valves.

It will be seen that advantage is taken of the large size of the CAT27 to use rather more filament power than is necessary and to operate the filament at a lower temperature to achieve the same peak emission. It is to be expected by this means that the life of the CAT27 will be considerably longer than that of the 3Q/294E, and the increased life and less frequent maintenance changes of the longer-life valve have to be considered against the cost of the additional filament power consumed. Owing to the unusually long lives of these valves, it will be many years before an exact comparison of costs can be made.

(3.1.2) BW165.

The BW165 is used for two distinctly different purposes:

(*a*) As the main power amplifier in the high-power television transmitters at Sutton Coldfield, Wenvoe, Kirk o'Shotts and Holme Moss (Band I).

(*b*) In the oversea broadcasting service from the Ludlow transmitter, where they are used both as power amplifiers and modulators in the short-wave band.

For these services the BW165 takes the place of the American 880 type or its counterpart, the CAT21, both of which are fitted with bright tungsten filaments. They have the following filament characteristics:

	V_f volts	I_f amp
BW165	7·2	170
880	12·6	320
CAT21	12·5	320

The change-over from the tungsten-filament valves to the thoriated-tungsten BW165 is a very simple operation, the lower filament voltage being obtained usually by altering the transformer primary connections.

(3.1.3) BR161.

The BR161 is used as a power amplifier and modulator in the Daventry Third Programme transmitter in place of the bright tungsten-filament valve BR126. The two valves are directly interchangeable, except for the filament characteristics which are as follows:

	V_f volts	I_f amp
BR126	12·5	480
BR161	9	175

The change-over presents no problems, the lower voltage being obtained by tappings on the filament transformer primary.

(3.1.4) 3Q/260E.

The 3Q/260E was the first high-power valve with a thoriated filament to be used in the B.B.C. service. During alterations some years ago to the London Home Service transmitter at Brookman's Park, opportunity was taken to introduce the valve as a cathode-follower and to note the performance of a thoriated filament under high-power conditions. Although as a cathode-follower the valve is lightly loaded, it has performed admirably.

(3.1.5) CAT30.

The CAT30 is used in place of the bright tungsten valve CAT20C, which is used as a modulator in the oversea broadcasting transmitters now using the CAT27 in place of the CAT17C. The filament voltage of the CAT30 is the same as the CAT27, i.e. 17·5 volts, so that, by using a pair of CAT27 valves in place of a pair of CAT17C, and a pair of CAT30 valves in place of a pair of CAT20C, the busbar voltage of the transmitter can be reduced from about 33 volts to about 20 volts.

This overall reduction in power consumption is very considerable and is dealt with in more detail in Section 4.

(3.2) Performance Results in Service

The standard of performance required from valves used in broadcasting is very high and can be conveniently expressed in terms of reliability as a function of the programme time lost due to valve failure. This is illustrated over the past few years by Fig. 6, which includes loss of programme on all B.B.C. Services, l.f., m.f., h.f., and v.h.f. The introduction of thoriated filament valves for test has therefore been undertaken gradually so that no serious deterioration in reliability would occur owing to unforeseen factors. Thoriated transmitting valves have now been introduced for extended life tests in short-wave, medium-wave and television transmitters. A detailed analysis of the results, both as regards life and reliability, is given below.

CAT27.—The valve has been installed in 29 operational sockets, 25 operating under class-C anode-modulated short-wave conditions. 24 of these valves are operating at $V_a = 11$ kV, $I_a = 5$ amp. One valve operates at $V_a = 11$ kV, $I_a = 7$ amp. The remaining four valves are operating as class-B linear r.f. amplifiers at medium frequency ($V_a = 16 \cdot 5$ kV, $I_a = 6 \cdot 4$ amp). The performance obtained is as follows:

Valves in use	Peak life to date	Average running period	Number of failures
29	>32 000 h	>13 000 h	1

The one failure was due to a broken filament bracing wire at a life of 3 486 h.

CAT30.—The valve has been installed in 14 operational sockets all operating as class-B l.f. amplifiers ($V_a = 11$ kV). The performance obtained is as follows:

Valves in use	Peak life to date	Average running period	Number of failures
14	>19 000 h	>11 700 h	3

G–F	Low emission	Others
—	—	100%

3Q/294E.—The valve has been installed in 24 operational sockets all operating as class-C anode-modulated at high frequencies ($V_a = 10 \cdot 6$ kV, $I_a = 6 \cdot 5$ amp). The performance obtained is as follows:

Valves in use	Peak life to date	Average running period	Number of failures
24	>15 000 h	>7 900 h	21

G–F	Low emission	Others
76%	5%	19%

3Q/260E.—The valve has been installed in six operational sockets operating as very-low-frequency cathode-followers feeding a class-B modulator ($V_a = 12$–13 kV). The performance is as follows:

Valves in use	Peak life to date	Average running period	Number of failures
6	>20 000 h	>9 100 h	10

G–F	Low emission	Others
10%	50%	40%

BW165.—The valve has been installed in 30 operational sockets, 22 operating as class-C anode-modulated h.f. amplifiers and eight operating as linear amplifiers at television Band 1 frequencies. The performance is as follows:

Operating at $V_a = 10$ kV and $I_a = 3 \cdot 5$ amp.

	Valves in use	Peak life to date	Average running period	Number of failures
Short-wave	22	>33 000 h	>15 000 h	42

G–F	Low emission	Others
12%	57%	31%

Operating at $V_a = 8$ kV and $I_a = 2 \cdot 5$ amp:

	Valves in use	Peak life to date	Average running period	Number of failures
Television	8	>22 000 h	>6 000 h	32

G–F	Low emission	Others
6%	75%	19%

BR161.—Installed in 16 operational sockets, eight operating at low frequency class-B, and eight operating at low-frequency class-C anode-modulated ($V_a = 10$ kV, $I_a = 2 \cdot 5$ amp). The performance is as follows:

Valves in use	Peak life to date	Average running period	Number of failures
16	>20 000 h	>16 000 h	20

G–F	Low emission	Others
30%	60%	10%

In existing installations using tungsten-filament valves it has been the custom to maintain a graduated schedule of filament voltage, increasing with life according to the type of valve.

The thoriated-filament valves listed have all been operated throughout life at constant voltage, but there is some evidence to favour operation at constant power as the thoriated-tungsten-filament resistance changes with life.

Table 1

SUMMARY OF PERFORMANCE

Valve type	Cooling	Number in use at one time	Frequency band	Peak life	Average running period	Failures
				hours	hours	
CAT27	Water	29	H.F.	>32 000	>13 000	1
CAT30	Water	14	V.L.F.	>19 000	>11 700	3
3Q/294E	Water	24	H.F.	>15 000	> 7 900	21
3Q/260E	Water	6	V.L.F.	>20 000	> 9 100	10
BW165	Water	22	H.F.	>33 000	>15 000	42
		8	V.H.F.	>22 000	> 6 000	32
BR161	Air	8	L.F. V.L.F.	>20 000	>16 000	20

(3.2.1) **Survivor Curves.**

Survivor curves of a typical tungsten-filament valve and thoriated-tungsten-filament valve are shown in Fig. 7. The precipitous initial fall in the curve for thoriated tungsten filament is explained by the incidence of mechanical faults as described in Section 1. It is reasonable to conclude that, when these early catastrophic failures are eliminated by suitable design modifications, the general shape of the two curves will be similar.

(4) A STUDY OF THE ECONOMIES OF THORIATED FILAMENTS IN PRACTICE

In existing installations using plain tungsten-filament valves, the operating costs may be divided under two headings:

(*a*) The cost of converting existing installations from tungsten-filament valves to thoriated-tungsten-filament valves.

(*b*) The savings brought about by reduced filament power consumption of the thoriated valve.

The capital cost of conversion varies widely, depending on whether the valve is a direct replacement both mechanically and electrically for the tungsten-filament valve. Valves CAT27, CAT30 and CAT29 are of this type, and the cost of converting a 100kW h.f. transmitter is approximately £50. This is made up mainly of recalibration of meters and alteration to protective relay circuits. Where the valves are supplied from transformers, usually of the surge-limiting type, the cost is likely to be considerably increased. In the case of valve type 3Q/294E, which requires the fitting of a new valve jacket and various other mechanical alterations, the cost of converting a 100kW h.f. transmitter is £400. The estimated savings in filament power of the thoriated valve compared with the tungsten-filament valve is tabulated in Section 4.2. However, in no case have the final average life figures for the thoriated valves been established, and the total savings have therefore still to be established. It may well be that these will be considerably increased as more information becomes available.

(4.1) Mechanical Aspects

The need for interchangeability in existing equipment of the thoriated-tungsten-filament valves has already been referred to, in order to reduce the capital cost of conversion. However, existing stocks of tungsten-filament valves have to be consumed, and, in addition, it is not usually possible to remove from service any of the equipment which is to be converted, except for a very short period. Various mechanical equipment used for handling valves, such as valve trucks, etc., should also be easily adaptable to handle the thoriated valves. There is thought to be a tendency for the thoriated valve to be more fragile than the tungsten equivalent, and the incidence of breakage in transit is being carefully watched to establish the need for any special packing or handling arrangements.

(4.2) Electrical Compatibility

When considering the conversion of existing tungsten-filament installations to thoriated-tungsten-filament valves, the source of filament power supply is important. In older installations, where motor generators are often used, no difficulty has been encountered in altering the output voltage and current over a wide range. However, voltage regulators and protective devices have required modification where the operating voltage of the thoriated valves have differed from that of the plain tungsten filament.

Savings in Filament Heating Power with Thoriated Tungsten Filaments compared with Pure Tungsten Filaments

CAT27	66%
3Q/294E	83%
CAT30	68%
3Q/260E	63%
BW165	69%
BR161	76%

In a typical installation of four 100kW short-wave transmitters converted to thoriated tungsten filaments, the net power savings have been measured as 156kVA on maximum demand per annum and 751MWh per annum. This is equivalent to 13% reduction in maximum demand for the complete installation and 18% reduction in the total power consumption.

(5) CONCLUSION

The authors consider that there has now been sufficient experience in the use of valves with thoriated tungsten cathodes to recommend their extended use in all future equipment. It is possible that the full potentialities of thoriated tungsten cathodes have not yet been attained, and that, with improvements in vacuum technique and getters, the much greater emission which is available can be more fully exploited. This will result in more compact valve designs, for use particularly at the higher frequencies. It seems unlikely that, for the type of valve covered in the paper, the carburized thoriated tungsten cathode will be superseded by any other form of emitter for some years to come.

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