Design and Operational Characteristics of Thoriated Tungsten Filaments in High Power Valves

J. ZIEGLER, B.Sc.*

*Amalgamated Wireless Valve Co. Pty. Ltd.

Design and Operational Characteristics of Thoriated Tungsten Filaments in High Power Valves

J. ZIEGLER, B.SC.

Abstract

The thoriated tungsten cathode is described, and the nature of the physical processes associated with it indicated. An account is given of a typical method of arriving at a design of a filamentary thoriated tungsten cathode for a valve, and a method is developed for solving the problem of making adjustments to a design for any given set of compatible requirements. Operating practices are discussed, in relation to both the strong dependence of emission life upon applied filament voltage, and the influence of traces of residual gas.

1. Introduction

The chief properties of thoriated tungsten responsible for its wide use as an electron source in electron tubes of high power are, firstly, its good emission efficiency in terms of milliamps per watt when compared to pure tungsten, and secondly, its ability to withstand high anode voltages, when compared to the alkaline earth oxide cathode as used in smaller valves.

Thoriated tungsten has been used as an emitter for many years and the principles of its application are well known. It consists of tungsten in which is dispersed a small quantity of thoria—of the order of 1% or 2% by weight. Because of its mechanical properties, it is usual to employ it in the form of drawn wires of round section. The wire is partially converted to di-tungsten carbide (W_2C), commonly by heating the wire to about 2300°K in an atmosphere containing a hydrocarbon gas or vapour such as ethylene, toluene, xylene, etc., the step being referred to as carburizing. A carburized wire has a core of thoriated tungsten and an outer shell of di-tungsten carbide in which thoria is dispersed. See Figs. 1 and 2.

A thoriated tungsten emitter is usually operated at a temperature in the vicinity of 2000°K (1727°C), when a good emission life is realised together with a reasonable emission efficiency. The emission efficiency of pure tungsten is about 10 mA/watt : that of thoriated tungsten is some 100 mA/watt, whilst that of the alkaline earth oxide cathode is in the order of 1000 mA/watt. The emission life depends upon both the amount of carbide and the operating temperature. Figs 4 and 5 describe this dependence as found by experiment.

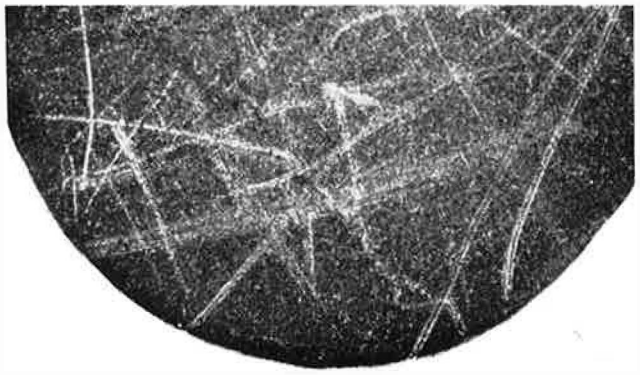

Figure 1.—*Section of part of an uncarburized thoriated tungsten wire. (Cf. Figure* 2.)

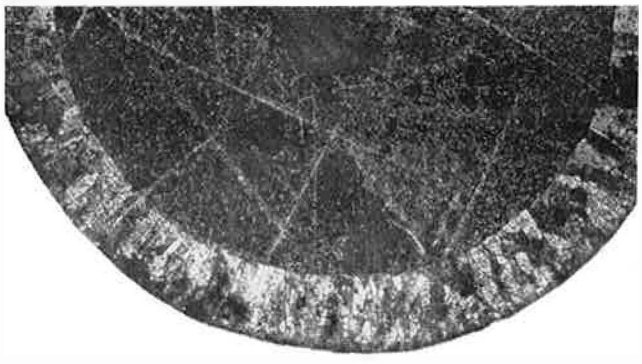

Figure 2.—*Section of part of a carburized thoriated tungsten wire showing layer of* W_2C.

Note. Figs. 1 and 2 have been retouched to eliminate the mounting medium and edge detail is therefore impaired. Long white lines are scratches due to imperfect polishing of the specimens.

2. Physical Processes

It is generally accepted that the lowering of the work function of tungsten by the addition of thoria to the wire is caused by the presence of a layer, perhaps less than a complete monolayer, of thorium atoms on its surface. This thorium is produced by chemical dissociation of the thoria within the wire, tungsten carbide acting as the reducing agent, and probably takes place principally at temperatures reached during manufacture[1]. It has been suggested[2] that it may also take place slowly and continuously at filament operating temperature during the service life of the valve, the thorium diffusing to the surface. Continuous replenishment of thorium at the surface, at least by diffusion, would be necessary in order to replace that slowly removed from the surface by evaporation and positive ion bombardment. The rates of dissociation, diffusion, and removal as well as the quantity of thoria stored in the wire are such that, for operation within the range 1950-2050°K, the end of useful emitting life of a thoriated tungsten filament is not likely to be governed by the original amount of thoria.

The fact that the presence of carbide not only produces, but is necessary to maintain the lowering of the work function of tungsten, conferred by the addition of thoria, was originally explained[1, 2, 3] by attributing to the carbide layer the action of resisting the outward diffusion of thorium : thus dispensing thorium at a rate sufficiently slow to prevent its exhaustion within a reasonable life span. It would appear to have been demonstrated[4] that this is not the explanation : that the carbide acts rather as a preferred target for attack by residual gas left in the valve after even the most careful pumping schedule, in this way tending to protect the thorium layer. Thus, the emission life of a thoriated tungsten emitter, upon which information is given in Fig. 4, comes to an end when substantially all of the protective shell of di-tungsten carbide has been converted back to tungsten. Valves with thoriated tungsten emitters which have reached the end of their emission life have little or no carbide left on the filament.

Jenkins and Trodden[4] have investigated reactions between W_2C and various residual gases. One is struck by the thought that residual gases would be responsible for converting to tungsten many milligrams of W_2C in a typical valve. It is inconceivable that sufficient mass of gas be available for this in a modern high power valve without supposing a recurrent cycle of some sort. On this supposition, a gas capable of reacting in this way need have only a minute pressure in order eventually to remove all the combined carbon from the filament.

A question arises as to the nature of the gas and the reaction cycle. Data in Ref. 4 indicate that the three gases O_2, CO_2 and H_2O react with W_2C to form W and CO, and H_2 as well in the case of H_2O. It is tempting to surmise that, under conditions obtaining in the valve, hydrogen and carbon monoxide may react to form water vapour and free carbon. One could then posit the cycle:

$$H_2O + W_2C \longrightarrow 2W + \underbrace{CO + H_2}$$

$$\downarrow$$

$$H_2O + C$$

the carbon being deposited on various surfaces in the vacuum.

Raising the temperature of a filament would be expected to increase the rates of diffusion and removal of thorium as well as the rates of the several chemical reactions. All of these effects would result in reduced life, and Fig. 5 indicates the extent of this reduction.

Lowering filament temperature would, conversely, increase life, at least for moderate temperature changes. However, if the temperature is reduced sufficiently, one might question whether the changed rates of replenishment and removal of thorium would maintain enough of it on the surface over a long period to preserve the efficiency of electron emission. The indications from experience are that the work function does indeed tend to decrease steadily with time in such a case: thus one cannot rely upon extrapolating Fig. 5 to lower temperatures to predict increased life, and a valve so run may gradually lose much electron emission while retaining some W_2C. It would be expected that treatment at a suitably elevated temperature, such as used in manufacture to form the thorium layer, would then re-establish the emission, and this, too, agrees with experience.

3. Design

At one time, it was customary to design a thoriated tungsten emitter empirically. However, the method described below (or variations of it) is well known and would now be used almost universally. Cf Ref. 3.

A filament in this context refers to a cathode consisting of either one strand of wire, or several connected in parallel: choice of the number of strands will be influenced by such factors as constructional requirements, valve geometry, and the desired filament rating.

There are six principal quantities to be considered, viz.

The voltage applied to a strand,	E volts
The current in a strand,	I amps
The radius of a strand,	r cm
The length of a strand,	l cm
The operating temperature,	T°K
The fraction of area of cross section converted to W_2C	c

1. Schneider, P., "The Thermionic Emission of Thoriated Tungsten", *Journ. of Chemical Physics*, **28**, April 1958, 675-682.
2. Walker, H. S., Aldous, W. H., Roach, R. G., Webb, J. B. and Goodchild, F. D., "High Power Transmitting Valves with Thoriated Tungsten Filaments for use in Broadcasting", *Proc. I.E.E.*, **107**, (Part B), March 1960, 172-180.
3. Ayer, R. B., "High-Power Industrial Vacuum Tubes having Thoriated-Tungsten Filaments", *AIEE Trans.*, **72**, (Part 1), May 1953, 121-125.
4. Jenkins, R. O. and Trodden, W. G., "The Poisoning of Thoriated Tungsten Cathodes", *Journ. of Electronics and Control*, **12**, Jan. 1962, 1-12.

One begins a filament design knowing the maximum instantaneous cathode emission required by the design of the valve. One then allows a safety factor of perhaps four or five times this maximum emission figure. Reference to information such as that contained in Fig. 3 yields the necessary wattage rating to achieve the emission desired. A safety factor of the magnitude allowed is necessary because the work function of a substance, upon which its electron emission depends, is determined by the outermost layer of atoms at its surface. The work function of a composite material like thoriated tungsten is therefore not a quantity that lends itself to being reproduced with precision from one sample to the next.

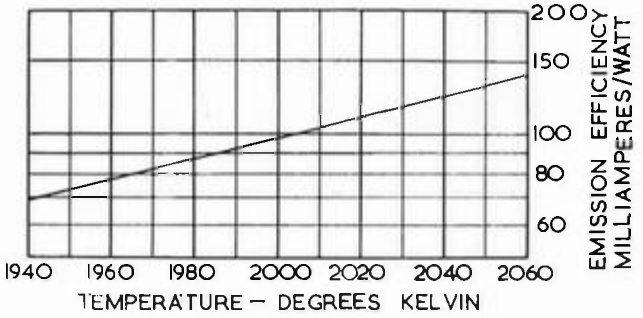

Figure 3.—*Emission efficiency of carburized thoriated tungsten as a function of temperature. (Drawn from values quoted by Dushman, Int. Crit. Tab., Vol.* 6, 1929, *p.* 55, *and the value for* ϵ *for* W_2C (*equation* 1) *quoted in Ref.* 5.)

Note. This curve describes total electron emission values, and represents average figures. As noted in the text, rather wide statistical divergences from it are to be expected.

It is sufficiently accurate to assume that all of the electrical power dissipated in the filament strand is radiated from its surface in accordance with the Stefan-Boltzmann radiation equation. One can then write

$$EI = S\epsilon T^4 \times \text{surface area of a strand}$$
$$= 2\pi S\epsilon r l T^4 \qquad (1)$$

where S = Stefan-Boltzmann constant ($=5.73 \times 10^{-12}$ watt cm^{-2} $degree^{-4}$)

ϵ = power emissivity of the surface (taken[5] as 0.35 for carburized thoriated tungsten near 2000°K).

T = temperature in degrees K.

We may assume an operating temperature of 2000°K. Reference to Figs. 4 and 5 will lead to a choice, based on considerations of life, of the area percentage of carbide to be used in conjunction with wire of a given diameter.

It may be questioned why substantially all of the wire is not customarily converted to di-tungsten carbide, as this would result in the best life obtainable from wire of a given size operating at a given temperature. Whilst there would be technological difficulties in attaining the proper type and formation of tungsten carbide, the principal objection is that as the percentage of carbide increases the wire becomes more and more brittle, to the point where it becomes impracticable to transport the finished valve.

The next step is to choose the voltage rating, E, of the filament strand. This also fixes its hot resistance, and one may then relate this to the area percentage of carbide that will be used and the conductivities at 2000°K of thoriated tungsten and di-tungsten carbide[2].

Taking

σ_f = "average" conductivity measured in the axial direction of a carburized filament strand

σ_{th} = conductivity of thoriated tungsten

σ_c = conductivity of W_2C

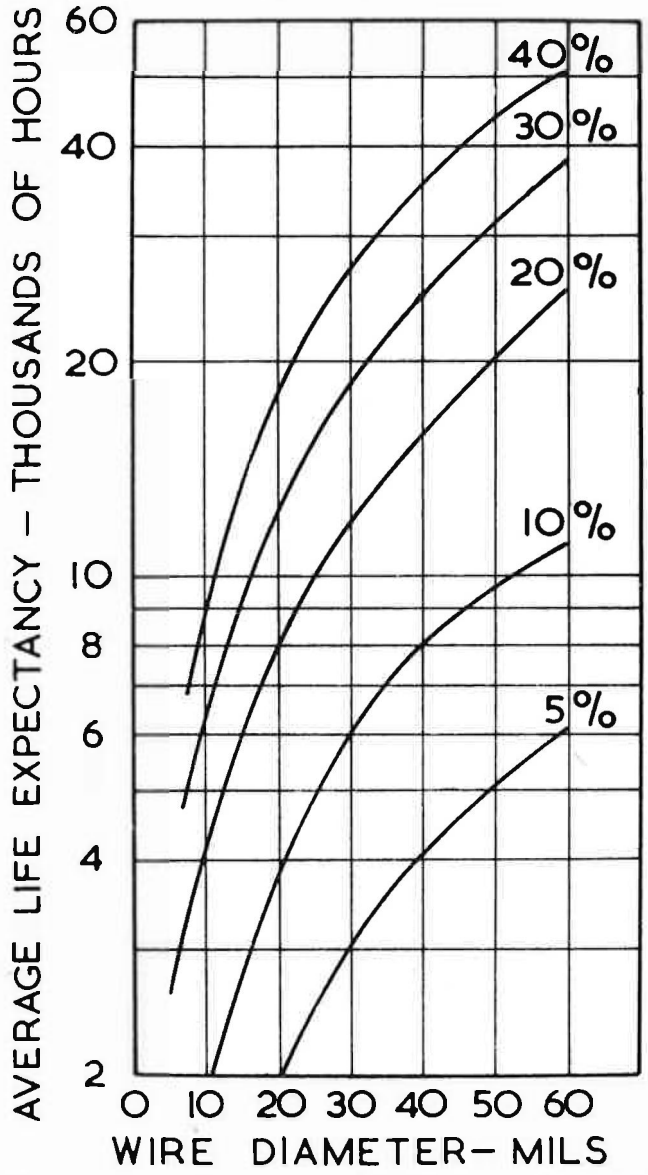

Figure 4.—*Average life expectancy at* 2000°*K of carburized thoriated tungsten filaments as a function of wire diameter and the percentage of area of cross section converted to* W_2C. (*Taken from Ref.* 3, *based on life test data.*)

Note. Individual valve lives would be expected to show rather wide statistical divergences from these curves. Cf. also discussion of this point in Ref. 2, wherein it is stated that these data "almost certainly underestimate the life that can be obtained from modern cooled-anode valves" (p. 175).

5. Dailey, H. J., "Designing Thoriated Tungsten Filaments", *Electronics*, 21, Jan. 1948, 107-109.

6. Knoll, M., "Materials and Processes of Electron Devices", pub. 1959 by Springer-Verlag, Berlin/Gottingen/Heidelberg.

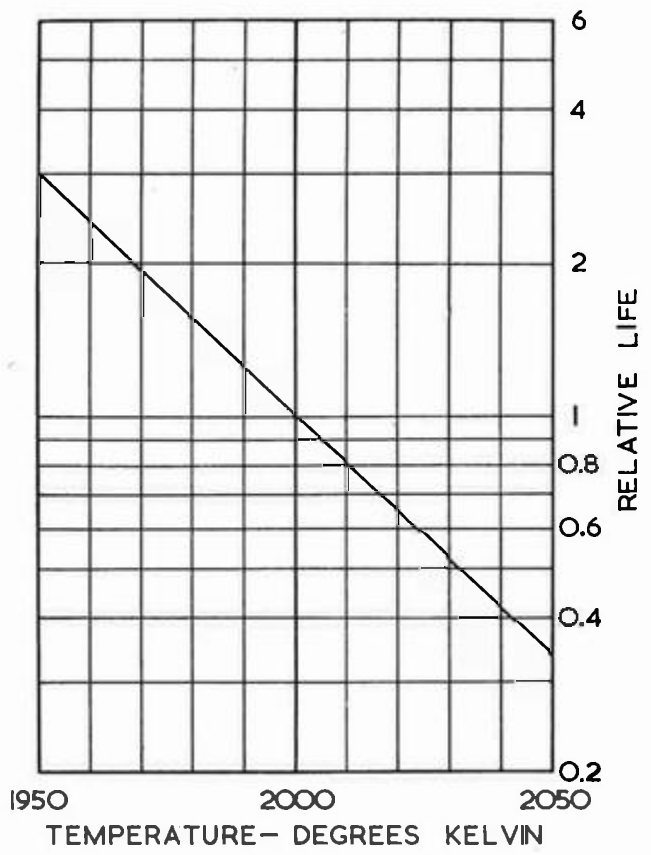

Figure 5.—Relative life as a function of temperature for carburized thoriated tungsten, based on measured rates of loss of carbon. (Drawn from data given in Refs 2 and 3.)

and using subscripts to indicate temperature in degrees Kelvin, there is the relation

$$\sigma_{f_{2000}} = \sigma_{W_{2000}} - c(\sigma_{W_{2000}} - \sigma_{c_{2000}}) \qquad (2)$$

One then has

$$\frac{E}{I} = \frac{l}{\pi r^2 \sigma_{f_{2000}}} \qquad (3)$$

for the carburized filament strand at 2000°K.

Values quoted for the conductivities of thoriated tungsten and of W_2Care^2 (in units of 10^3 ohm^{-1} cm^{-1})

$\sigma_{c_{2000}} = 8.48$; $\sigma_{W_{2000}} = 17.9$; $\sigma_{c_{293}} = 12.5$; $\sigma_{W_{293}} = 182.$

Solving equations 1 and 3 simultaneously yields the length and diameter of the filament.

The method described is approximate and ignores various corrections, but does lead to results that are quite satisfactory in practice. It is, however, worth digressing to consider one point ignored in the above discussion : the cooling of the ends of the filament strand by thermal conduction to their supports. Notice that the designed operating temperature and percentage of carbide are derived from the application of Ohm's law to the filament strands: thus yielding some sort of average temperature and average carbide percentage (the carbide percentage is customarily calculated from resistance readings of the filament wire taken before and after carburizing). Now, referring to Fig. 5, it is clear that the life of the filament is a very rapidly changing function of the temperature : and the temperature must vary along the length of the wire due to end cooling effects. Thus, one might expect the designed averaged temperature to yield a poor prediction of the life of the filament.

However, during carburizing, when the wire is heated by passage of current, the centre of the wire is also hotter than its ends. This leads to a greater rate of combination of carbon with tungsten, and one finds that the shell of di-tungsten carbide in the middle of a strand is thicker than towards the ends. Thus there is more carbide in the hotter part of the wire, from which it also disappears more rapidly in service, the final result being that the variation in temperature tends to be offset.

Whilst the above method yields a good basic design, it is none the less true that small adjustments may be necessary : for example, to allow for temperature effects due to the close proximity of filament strands to one another, or to take into account manufacturing tolerances. Such adjustments may be carried out empirically, and it is usual to do so.

4. Variations in Design

Sometimes simultaneous adjustments must be made in several filament parameters whilst leaving others fixed. It might happen, for example, that one wishes to reduce the filament operating temperature whilst increasing the carbide percentage, and perhaps also making provision for the use of a new batch of filament wire having a slightly different diameter. In accommodating these variations, it might be necessary to keep the filament rated voltage unchanged, since it is usual to operate filaments at constant voltage, whilst the filament wire length and current at the rated voltage may be allowed to vary. An emprical approach to a solution of this sort of problem consumes a great deal of time and expense, whilst on the other hand it is not convenient to use the design equations given earlier.

At A.W.V. we have devised a convenient method for making design adjustments.

One begins by writing

$$W = \frac{EI}{2\pi rl} \qquad (4)$$

where W = radiated watts/cm^2;

also

$$W \times \text{surface area} = \frac{E^2}{\text{Wire resistance}} = \frac{\pi r^2 E^2 \sigma_f}{l} \qquad (5)$$

Whence

$$W = \frac{rE^2\sigma_f}{2l^2} \qquad (6)$$

Equations 4 and 6 may be written :

$$\log W = \log E + \log I - \log r - \log l - \log \pi - \log 2 \qquad (7)$$

and

$$\log W = \log r + 2\log E + \log \sigma_f - 2\log l - \log 2 \qquad (8)$$

It is then readily shown that

$$\frac{\Delta W}{W} \approx \frac{\Delta E}{E} + \frac{\Delta I}{I} - \frac{\Delta r}{r} - \frac{\Delta l}{l} \qquad (9)$$

and

$$\frac{\Delta W}{W} \approx \frac{\Delta r}{r} + \frac{2\Delta E}{E} + \frac{\Delta \sigma_f}{\sigma_f} - \frac{2\Delta l}{l} \qquad (10)$$

where Δ signifies a finite increment.

The operating temperature and percentage of carbide together determine the conductivity σ_f of the filament. One may now plot relative variations in σ_f as a function of both the temperature and the carbide percentage, assuming knowledge of conductivities and their temperature coefficients. This has been done in Fig. 6. On the same figure has been plotted relative variations in the thermal emissivity W as a function of temperature. It is a convenient circumstance that the latter, over the fairly narrow temperature range considered, approximates to a straight line, and is so drawn.

One may now consider relative variations, expressed for convenience as percentages, in the approximate equalities 9 and 10. Any changes in W and σ_f resulting from changes in the temperature or the percentage of area of cross section converted to W_2C (C%), may be read as percentages from Fig. 6.

An example of the type of problem mentioned at the beginning of this section may be used by way of illustration.

Example

It is required that the temperature be lowered 10°K, and C% is to increase 5%, while $\frac{\Delta r}{r} = -4\%$. ΔE must be zero.

Find $\frac{\Delta l}{l}$ and $\frac{\Delta I}{I}$.

From Fig. 6, for $\Delta T = -10°K$ and $\Delta C\% = +5\%$,

$$\frac{\Delta W}{W} = -2.0\% \quad \text{and} \quad \frac{\Delta \sigma_f}{\sigma_f} = 2.4\%.$$

Thus from (10)

$$\frac{\Delta l}{l} \approx -2.2\%$$

and from (9)

$$\frac{\Delta I}{I} \approx -8.2\%$$

5. Operating Practice

As mentioned, it is usual to design a thoriated tungsten filament to operate near 2000°K. In some applications, pulse modulators for example, high emission efficiency can assume great importance, and emission life may be sacrificed to achieve it by raising the operating temperature a hundred degrees or more above that value. However, the figure of 2000°K as a design figure yields reasonable life whilst being safely above temperatures at which the work function tends to decrease gradually.

It may be verified from the data presented that a change of about 4% in filament voltage (e.g. a fall) will change the temperature by 30°K (fall), leading to an emission

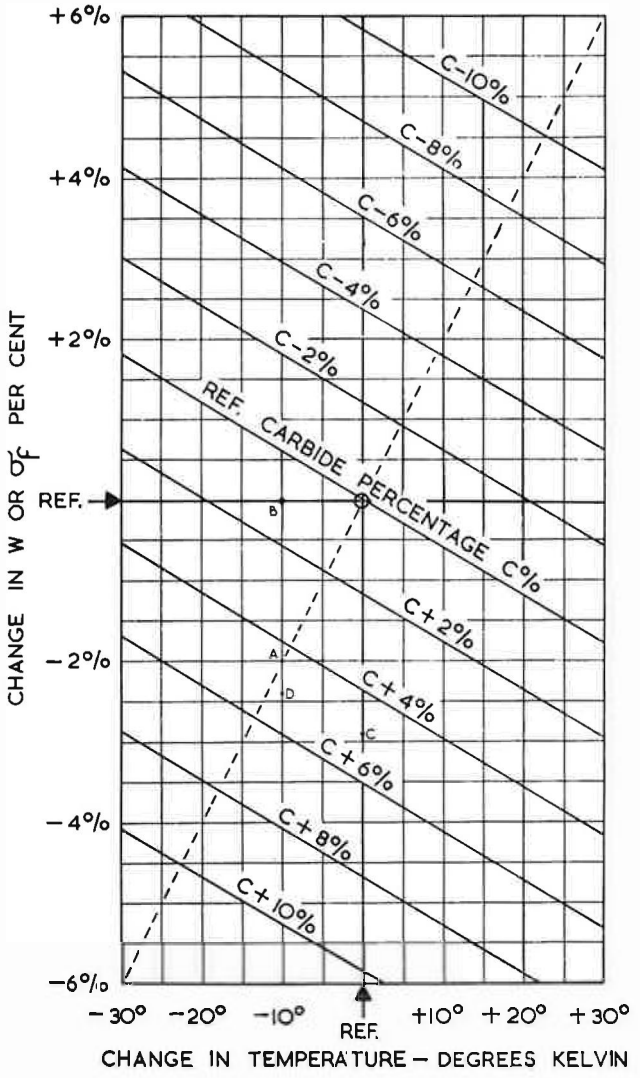

Figure 6.—Relative changes in thermal radiant emissivity W (dashed line) and filament conductivity σ_f (solid lines) as functions of changes in temperature and carbide percentage. The points and line marked "REF" are reference levels representing any starting point to which changes are to be referred.

Notes.

(a) Changes in W with temperature are calculated from equation 1.

(b) Equation 2 is used for calculating changes in σ_f with percentage of carbide, with the values given in the text for σ_W and σ_c.

For calculating changes in σ_f with temperature, the temperature coefficient of σ_W is taken as −6.05% per 100°K (from tabulated data in Ref. 6) : the temperature coefficient of σ_c is estimated as −2.35% per 100°K.

(c) For purposes of establishing the curves, reference levels for temperature and C% are taken as 2000°K and 20% respectively. However, for purposes of use, it is sufficiently accurate to use any typical value as reference.

Example of use.

Referring to the example in Section 4, and using the point 0 as origin :

(a) for $\Delta T = -10°K$, the interval AB represents $\Delta W = -2.0\%$

(b) for $\Delta C\% = +5\%$, the interval CO represents $\Delta \sigma_f$ with temperature unchanged. When, simultaneously, $\Delta T = -10°K$, the interval DB represents the required value of $\Delta \sigma_f$, i.e. −2.4%.

change of about 20% (fall) and a life change by a factor of 2 (rise).

Thoriated tungsten types are mostly intended for operation at constant voltage on the filament, since this suits circuit economy, and a tolerance of $\pm$ 5% is usually given in order to cater for operation without a well regulated supply. For operation during standby periods manufacturers generally recommend reduction of filament voltage by 5% from the nominal value : and in fact it is usually possible to operate the filament at this reduced voltage while the valve is drawing its normal anode current, because the emission reserve of the filament will permit cooling to the degree implied.

Clearly, if one decides, in the interest of greatly improved life, to operate near the lower limit of filament voltage, good regulation and an accurate measuring instrument are called for. Voltage measurements must be made at the valve filament terminals, the points to which the rating is referred.

It might be questioned whether it would be feasible to reduce the filament voltage below the lower rated limit, to the point where circuit performance is just not affected. Thus one might reduce filament voltage in a transmitter until changes in anode current or distortion begin to evidence themselves, then raise the voltage, say, 3% above that level. Such an operation, besides calling for precision, would obviously result in a voltage dependent in part upon both the filament characteristics of the individual valve and the peak instantaneous cathode current called for by the transmitter.

Such a plan will sometimes work. However, as discussed in Section 2, experience indicates that the desired benefit may not ensue due to gradual deterioration of the thorium layer.

It is mentioned earlier that residual gas in the valve plays a key part in the process culminating in loss of emission from the filament. It would be expected that anything tending to raise the pressure of this gas would thereby shorten the life of the valve, and this is indeed so. While space current is being drawn, gas molecules tend to become ionised and in this condition are much more likely to be gettered (sorbed) by various surfaces in the valve. During periods when no high voltages are applied to the valve the reverse process, desorption, takes place, and the pressure of the residual gas tends to rise slowly. It is for this reason that it is often recommended by manufacturers that thoriated tungsten types in storage be operated periodically, if not near their ratings, at least by drawing appreciable space current while some hundreds of volts applied to some electrode, to encourage ionisation, sorption, and thus reduction in pressure of the residual gas. (It should be remarked that the pressures involved are usually well below those at which an ionisation glow would be visible in the valve.) Such "exercising" would commonly be recommended for repetition at intervals of three to six months.

The foregoing is pertinent to the consideration of a practice sometimes adopted ; that of running a standby transmitter with filaments alight but with high tension off, to provide rapid changeover in the event of a fault in the main transmitter. Whilst reduction of filament voltage in such a case has been discussed, it is also to be considered that gas desorption takes place more rapidly from a heated surface : with internal surfaces heated by the filament the effects that take place during normal storage are accelerated. In such a situation it is better practice to apply high tension and draw space current for a period each day rather than each week or, worse, some longer interval.

6. Conclusion

The design of a thoriated tungsten emitter can be carried out readily by using the customary methods, such as the one described. Adjustments to a basic design can be achieved using the method presented here. A successful design represents a delicate balance between a number of closely related factors, some of which change quite rapidly with others. In particular, the emission life of a thoriated tungsten emitter is very sensitive to the applied voltage across the filament ends.

Whilst the achieving of a good average filament life from a valve design is largely in the hands of the manufacturer, the user can, by careful supervision, obtain better average life than if he were content to use the valve at its nominal rated filament voltage. Suitable exercising of valves in storage, and of those subjected to protracted periods of operation of the filament without high tension, is also advisable in the interest of good life.

General Reference

Jones, H. A. and Langmuir, I., "The Characteristics of Tungsten Filaments as Functions of Temperature", *General Electric Review*, **30**, June 1927, 310-193; July 1927, 354-361; Aug. 1927, 408-412.

Simmons Limited, Glebe, Sydney.

AMALGAMATED WIRELESS VALVE CO. PTY. LTD.

HEAD OFFICE: WIRELESS HOUSE, YORK STREET, SYDNEY

MELBOURNE
BRISBANE
ADELAIDE