

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

J. ZIEGLER, B.Sc.*

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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 $2300^\circ K$ 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 $2000^\circ K$ ($1727^\circ C$), 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.)

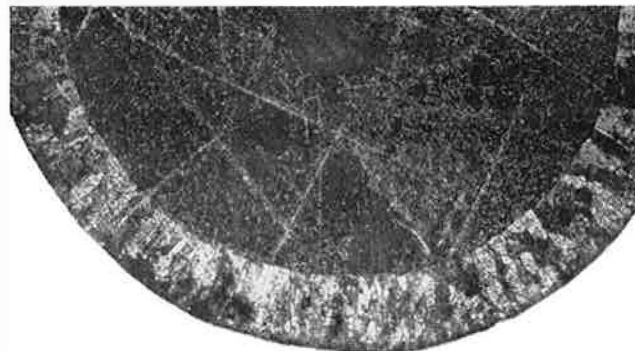


Figure 2.—Section of part of a carburized thoriated tungsten wire showing layer of W_2C .

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.

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.

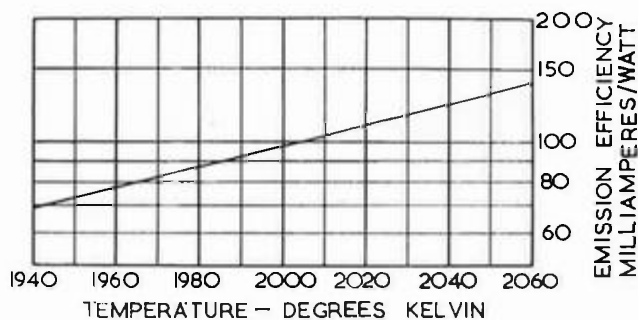


Figure 3.—Emission efficiency of carburized thoriated tungsten as a function of temperature. (Drawn from values quoted by Dushman, *Int. Crit. Tab.*, Vol. 6, 1929, p. 55, and the value for ϵ for W_2C (equation 1) quoted in Ref. 5.)

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

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

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

ϵ = power emissivity of the surface (taken⁵ 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 carbide²

Taking

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

σ_{tt} = conductivity of thoriated tungsten

σ_c = conductivity of W_2C

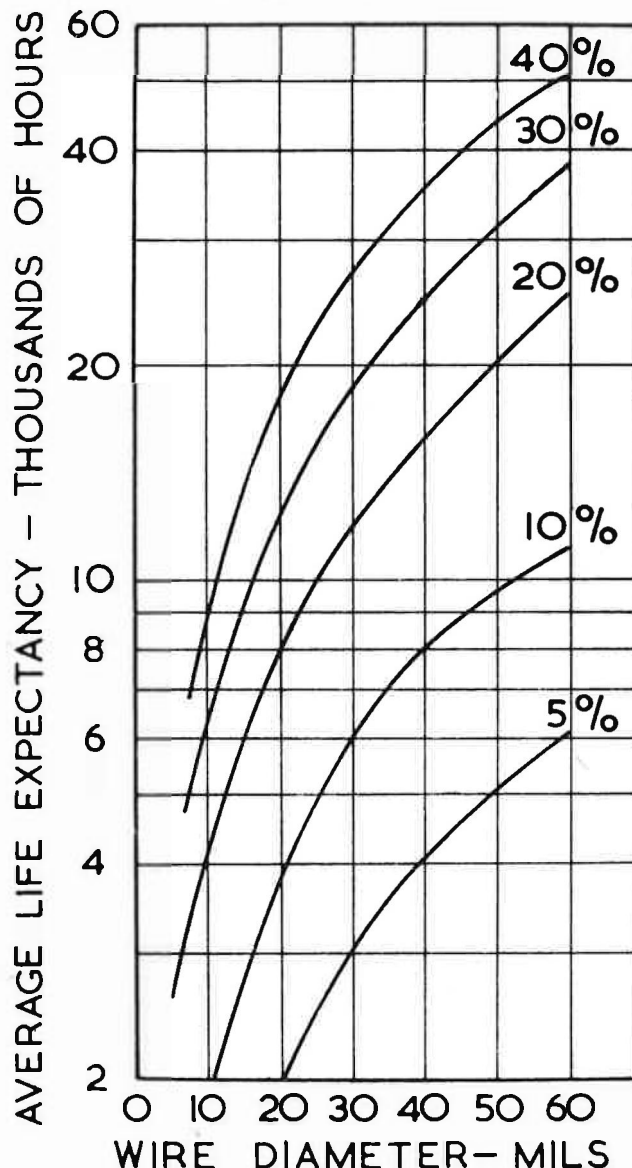


Figure 4.—Average life expectancy at 2000°K of carburized thoriated tungsten filaments as a function of wire diameter and the percentage of area of cross section converted to W_2C . (Taken from Ref. 3, based on life test data.)

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.

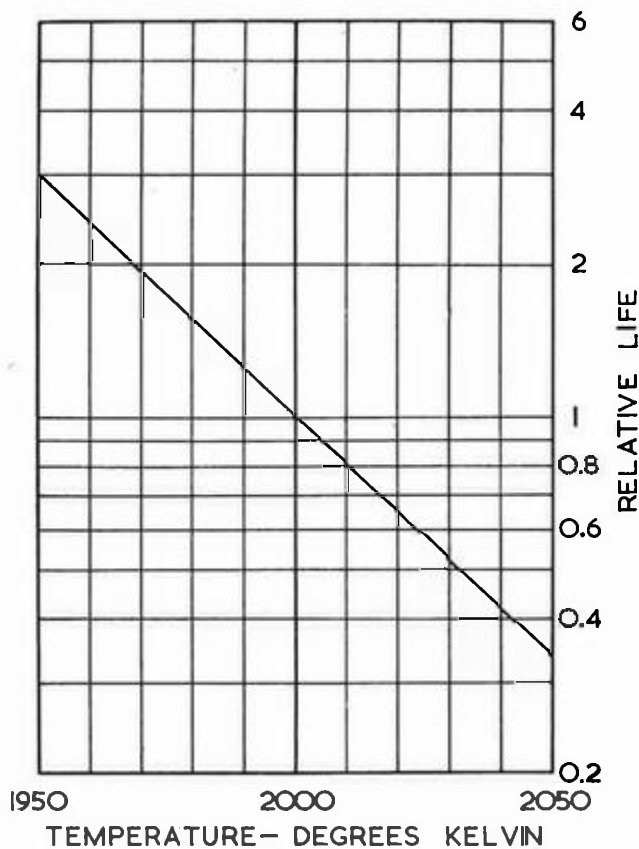


Figure 5.—Relative life as a function of temperature for carburized thoriated tungsten, based on measured rates of loss of carbon. (Drawn from data given in Refs 2 and 3.)

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

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

One then has

$$\frac{E}{I} = \frac{1}{\pi r^2 \sigma_{f_{2000}}} \quad (3)$$

for the carburized filament strand at 2000°K.

Values quoted for the conductivities of thoriated tungsten and of W_2Ca (in units of $10^3 \text{ ohm}^{-1} \text{ cm}^{-1}$)

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

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 empirical 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

$$W = \frac{EI}{2\pi r l} \quad (4)$$

where W = radiated watts/cm²;

also

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

$$\text{Whence } W = \frac{r E^2 \sigma_f}{2l^2} \quad (6)$$

Equations 4 and 6 may be written:

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

and

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

It is then readily shown that

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

