Designing Thoriated Tungsten Filaments

Design data for carburized thoriated tungsten filaments are calculated using formulas applicable to filaments of pure tungsten. Procedure requires controlled carburization to give carburized and uncarburized filaments similar electrical characteristics

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Until recently, the design of thoriated tungsten filaments was largely empirical. However, in 1937 it was observed that thoriated tungsten filaments made according to empirical design data gave filament temperatures agreeing within ±1 percent with the calculated temperature values for pure tungsten filaments. This discovery prompted further research which resulted in the formulas and data presented here.

Pure tungsten filaments require no carburization; thoriated tungsten filaments do require carburization and after being carburized have a higher resistance. Carburized filaments have greater thermal power emissivity than filaments of either pure tungsten or uncarburized thoriated tungsten. When the percentage of increased resistance resulting from carburization is equal to the percentage of increased power emissivity, a carburized filament will have some of the electrical properties of a pure tungsten filament; that is, the same current will heat both to the same temperature. For thoriated tungsten, this increased resistance is 1.2 times that which existed before carburization.

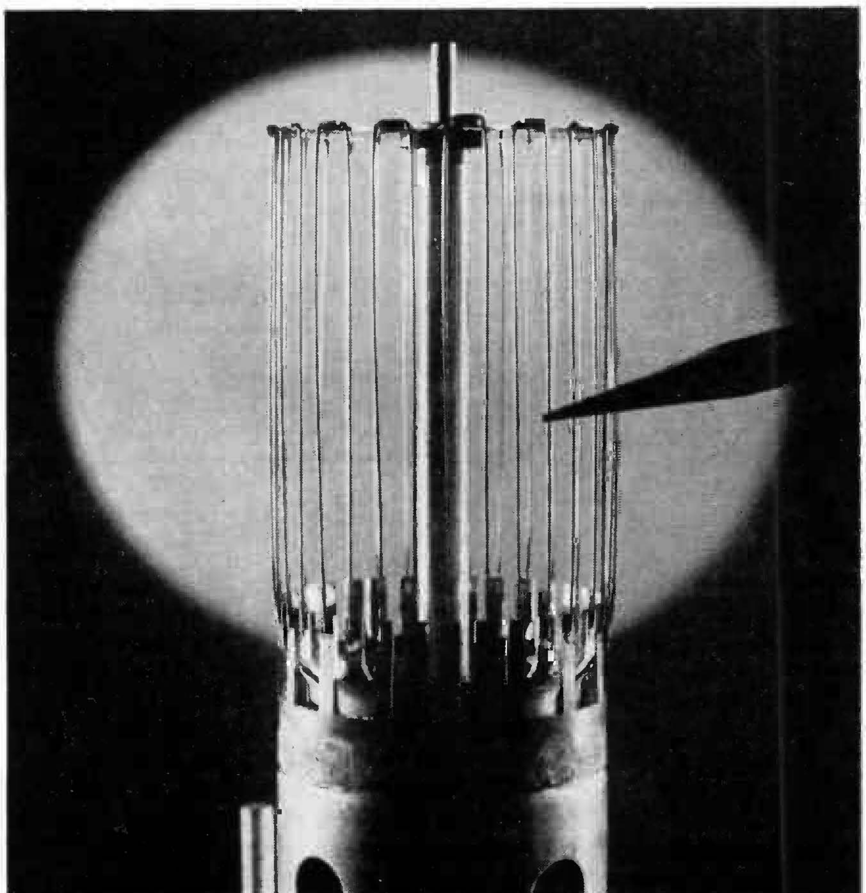
The power radiated into space from a straight wire may be expressed by

$$\eta = e_t \delta T^4 \qquad (1)$$

where η is equal to the power radiated in watts per sq cm per sec, e_t is the power emissivity of the surface at temperature T, δ is the Stephan-Boltzmann constant equal to 5.722×10^{-12}, and T is the temperature of the wire in degrees Kelvin. At 2,000 K, e_t is equal to 0.263 for pure tungsten[1] and $0.263 \times 1.2 = 0.315$ for the case of carburized tungsten[3].

Inspection of Eq. 1 reveals that when η is increased 20 percent by increasing the filament resistance by that percentage, and e_t is also increased by 20 percent due to filament carburization, for a given heating current T must remain constant. Therefore, Eq. 1 is applicable to either pure or carburized tungsten filaments for this set of conditions.

When it is desired to calculate the current required to heat a given tungsten wire to a particular tem-



This multiple hairpin filament of thoriated tungsten is typical of those used in high-power tubes for high-frequency industrial and broadcasting applications

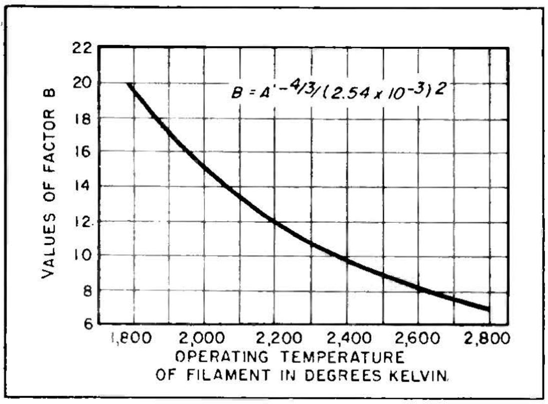


FIG. 1—The factor B, to be used in Eq. 5, is shown as a function of filament operating temperature

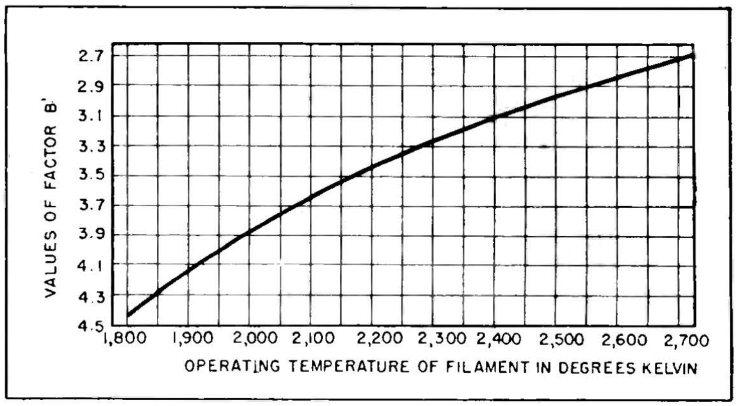


FIG. 2—The factor B', used in Eq. 6 to give filament wire sizes directly in mils, varies with operating temperature as shown

perature, the following expression[2] may be used:

$$Ad^{-3/2}=A' \qquad (2)$$

In this equation, A is the required current in amperes, d is the diameter of the wire in cm, and A' is the current required to heat a wire 1 cm in diameter to the given temperature. The appropriate value of A' is taken from values published by Jones and Langmuir[1].

As small filaments are usually specified in terms of the weight of a 200-mm length, the value of d used in Eq. 2 must be obtained from the relation

$$d=2.54\times 10^{-3}(W/K)^{\frac{1}{2}} \qquad (3)$$

in which d is the diameter in cm, K is a conversion factor varying with the wire density, and W is the wire weight in mg per 200 mm. Values of K for pure tungsten and for thoriated tungsten are given in Table I.

When Eq. 2 and 3 are combined, the following results:

$$2.54\times 10^{-3}(W/K)^{\frac{1}{2}}=A^{2/3}A'^{-2/3}.$$

Solving for W, one obtains

$$W = A^{4/3}KA'^{-4}\ (2.54\times 10^{-3})^{-2} \qquad (4)$$

or $W=A^{4/3}KB$ (5)

when $A'^{-4/3}\ (2.54\times 10^{-3})^{-2}$ is replaced by the factor B.

This relation holds for either pure or carburized thoriated tungsten when the correct conversion factor K is used for each. The carburized filament must be carburized to a 20-percent resistance increase at the rated current for Eq. 5 to hold rigorously. Values of B for various temperatures are given in Table II. They also appear in curve form in Fig. 1.

For the larger sizes of thoriated tungsten filaments, it is usually more convenient to measure the wire size directly in mils and to use the modified equation

$$d=A^{2/3}B' \qquad (6)$$

where d is the diameter in mils and A is the required heating current in amperes. Values for B' for various temperatures are given in Table II. They also appear in curve form in Fig. 2.

When a thoriated tungsten filament is carburized, the resistance is usually allowed to increase from 1.15 to 1.25 times the original resistance at the rated filament current. The power emissivity of the carburized surface normally does not change with the degree of carburization. Consequently, the temperature may be calculated over any range selected.

Let η_1 equal the power in watts required to heat a given filament that has been carburized to a 20-percent resistance increase; T_1 equal the calculated temperature of the above filament; η_2 equal the power in watts required to heat an identical filament that has been carburized to another resistance; and let T_2 equal the temperature of the second filament. The following equations may then be written:

$$\eta_1=e_t\delta T_1^4 \qquad (7)$$

$$\eta_2=e_t\delta T_2^4. \qquad (8)$$

Since e_t and δ are constant, upon dividing Eq. 8 by Eq. 7, one obtains

$$\eta_2/\eta_1=T_2^4/T_1^4. \qquad (9)$$

Because T_1, η_1, and η_2 are known, Eq. 9 is solved for T_2, yielding

$$T_2=T_1(\eta_2/\eta_1)^{1/4}. \qquad (10)$$

As an example, the wire size necessary for a filament that is carburized to give a voltage increment of 20 percent, operate at 2,000 K with a filament current of 10 amperes, and be made of thoriated tungsten wire containing 2 percent of thoria by weight is calculated from Eq. 5 and Tables I and II. Substituting values of K and B, $W=10^{4/3}\times 1.875 \times 15.06=610$ mg per 200 mm.

TABLE I—Values of Factor K for Various Filament Materials

Filament Material	Density in grams per cu cm	K
Pure Tungsten	19.06	1.931
1.0% Thoriated Tungsten	18.83	1.908
1.5% Thoriated Tungsten	18.73	1.898
2.0% Thoriated Tungsten	18.47	1.875

TABLE II—Values of B and B' for Various Filament Temperatures

Temperature in Degrees K	B	B'
1,800	19.68	4.44
1,900	17.14	4.14
2,000	15.06	3.88
2,100	13.37	3.65
2,200	11.93	3.45
2,300	10.76	3.27
2,400	9.69	3.11
2,500	8.82	2.97
2,600	8.07	2.84
2,700	7.41	2.72
2,800	6.83	....

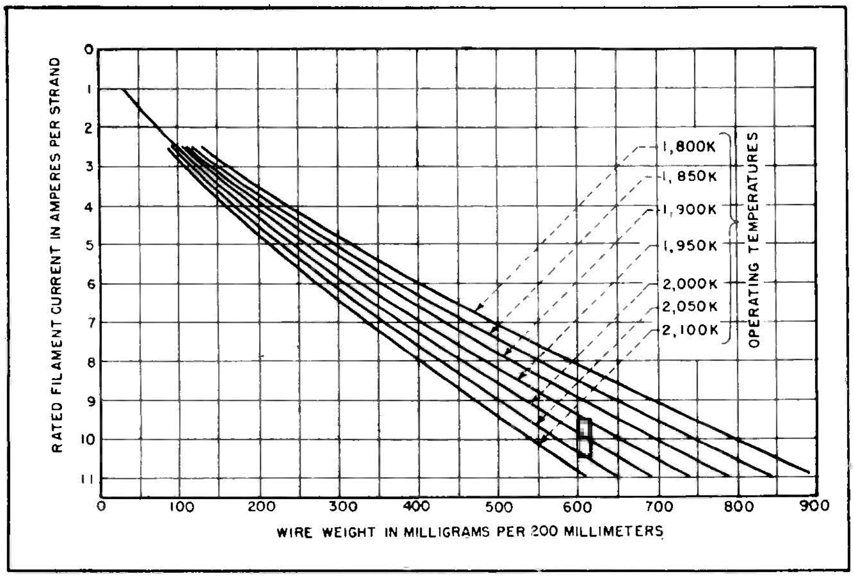


FIG. 3—Filament wire weight as a function of rated current for given operating temperatures. These curves are accurate for either pure tungsten or carburized thoriated tungsten filaments. Small rectangle outlines temperature deviations for example calculated

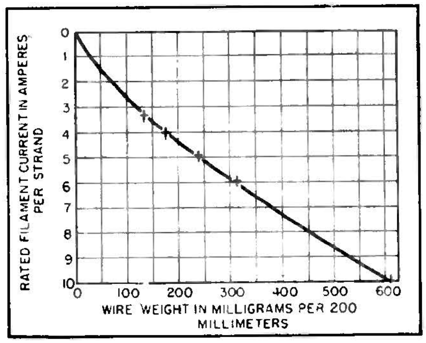


FIG. 4—Calculated curve of wire size as a function of rated filament current for a temperature of 2,000 K. Cross marks indicate filament sizes and current ratings determined empirically by the manufacturer. Length of horizontal line of each cross indicates tolerance on wire weight; length of vertical line indicates limits on filament current

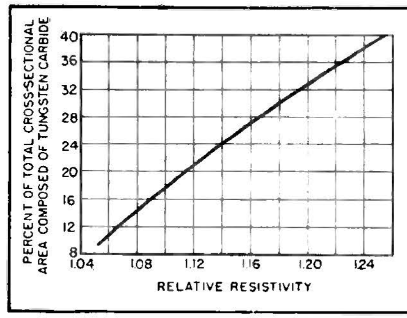


FIG. 5—Relative filament resistivity, or ratio of carburized to uncarburized resistivity, varies with percentage of tungsten carbide. Resistivity increase is determined by measuring increased voltage drop across filament carrying rated current

Assuming that the filament current limits are 9.5 to 10.5 amperes, the temperatures at those limits are calculated from Eq. 5 using Tables I and II and Fig. 1. Using the value of W calculated above, one obtains values of B equal to 16.12 for a filament current of 9.5 amperes, and 14.15 for a current of 10.5 amperes. From Fig. 1 the temperatures corresponding to these values of B are, for 9.5-ampere operation, $T = 1{,}948$ K, and for 10.5-ampere operation, $T = 2{,}052$ K.

The rectangle outlined in Fig. 3 shows the temperature variations resulting from both the variations in carburization and the necessary tolerance deviations in filament wire weight. Figure 3 covers the ranges of filament wire weight and filament current used for most thoriated tungsten filaments.

Figure 4 shows a curve calculated for 2,000 K with several filament wire weights and the corresponding current limits determined by Westinghouse after several years of experience.

The fragility of a given filament increases with the degree of carburization. Therefore, in considering this factor, use is made of Fig. 5 from which the percentage of filament cross-sectional area composed of tungsten carbide can be determined when the degree of carburization is known.

This analysis of filament design has been limited primarily to calculations of the heating current required for thoriated tungsten filaments. Data for end-loss calculations are given by Jones and Langmuir[1]. Although the calculations made here are rigorous only for those sections of filaments not affected by end cooling, experience indicates that the magnitude of error that arises from treating the entire filament by the data given here is usually less than the magnitude of normal manufacturing variations.

Table III presents a list of standard tubes with sizes of filament wire actually used, filament current limits, and calculated wire sizes at normal operating temperatures.

TABLE III—Calculated and Actual Filament Data for Several Standard Tubes

Tube Type	Calculated Operating Temperature in degrees K	Calculated Wire Weight in mg per 200 mm	Actual Wire Weight in mg per 200 mm	Filament Current Limits in amperes
204A	2,000	175	173–178	3.65–4.05
803	2,000	240	232–247	4.7 –5.3
833A	2,000	240	238–248	9.4 –10.3
849	2,000	99	97–100	4.75–5.25
860	2,000	137	138–144	3.1 –3.4
861	2,000	612	606–618	9.5 –10.5
891	2,540	45 mils	45 mils	57–62
895	2,560	51.3 mils	51.5 mils	66–72

REFERENCES

(1) H. A. Jones and I. Langmuir, The Characteristics of Tungsten Filaments as Functions of Temperature, *G-E Review*, p 310, June 1927; p 354, July 1927; p 408, Aug. 1927.

(2) W. E. Forsythe and A. G. Worthing. The Properties of Tungsten and the Characteristics of Tungsten Lamps, *Astrophysical Journal*, p 146, April, 1925.

(3) L. R. Koller, "The Physics of Electron Tubes", McGraw-Hill Book Co., Inc., p 83, 1937.