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ELECTRON-BOMBARDMENT FILAMENT DESIGNS FOR HEATING CYLINDRICAL THERMIONIC CONVERTERS

by Peter Cipollone

Lewis Research Center

Cleveland, Ohio

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ABSTRACT

The effect of axially varying the pitch of helical electron-bombardment heaters on the axial distribution of radial heat flux to an internally heated hollow cylinder was investigated; the cylinder simulating the electron-emitting electrode of a thermionic converter. Measured axial distributions of temperature and corresponding calculated heat fluxes are presented for a series of five variable-pitch filaments and for mean emitter-surface temperatures of 1778 to 2038 K. These results are compared to similar data obtained with a uniform-pitch filament.

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SUMMARY

An experimental evaluation of the effect of axially varying the winding pitch of helical electron-bombardment heaters on the axial distribution of the radial heat flux to an internally heated hollow cylinder is presented.

A series of filaments was wound and their geometry carefully characterized. They were then used to heat a hollow tantalum cylinder simulating the electron-emitting electrode of a thermionic converter. The axial distribution of temperature was measured on the outer surface of the cylinder, and the axial distribution of the radial heat flux was then calculated.

For the best filament, the radial heat flux was axially constant to within 20 percent over 85 percent of the cylinder's length for emitter-surface mean temperatures of 1806 to 2038 K. On the other hand, a helical filament of constant pitch resulted in axial variation in heat flux of approximately 150 percent over 85 percent of the cylinder's length for emitter-surface mean temperatures of 1778 to 1922 K.

INTRODUCTION

In a reactor in-core thermionic power system, the cylindrical fuel clad serves as the electron-emitting electrode of the thermionic converters. Heat is generated uniformly in the fuel pellet volume, resulting in a uniform axial distribution of radial heat flux along the inner surface of the emitter wall.

Thermionic converters are low-voltage, high-current devices. In such a power system, a number of converters would be electrically connected in series, and heat losses would occur by conduction through the series leads. Since these lead losses would typically be only a few percent of the total heat input, the axial distribution of heat flux along the outer surface of the emitter would also be quite uniform.

In order to accurately establish the performance levels of cylindrical converters by means of electrically heated out-of-core tests, it is necessary to simulate, as closely as possible, the uniform axial distribution of heat flux.

The preferred method of heating the emitting electrode in out-of-core tests is by electron bombardment from a helical filament. The filament, inserted into the central cavity of a hollow emitter, is electrically heated. Then a dc potential difference between the thermionic emitter and the filament accelerates electrons from the filament surface to the emitter, where the kinetic energy of the electrons is converted into thermal energy.

In such an arrangement, heat is lost by radiation from the central cavity and by conduction along the filament-support structure. In order to heat the emitter uniformly along its length, the filament design must compensate for these heat losses.

A helical filament of constant pitch was considered in reference 1, in which it was assumed that the filament could be represented by a hollow cylinder emitting electrons uniformly over its entire lateral surface. The analysis established the filament to cavity diameter ratio required to produce maximum heating efficiency but did not consider distribution of heat along the cylinder's axis.

Design of filaments to provide an axially uniform distribution of radial heat flux into the emitter has not previously been investigated. A succession of filament designs was therefore tested, the purpose being evolution of a filament design providing axially uniform heat flux.

Several helical electron-bombardment filaments with variations in winding pitch were evaluated experimentally. The filaments heated a hollow tantalum cylinder having a vapor-deposited rhenium outer surface. Emitter-surface mean temperatures ranged from 1778 to 2038 K. Axial distributions of temperature were determined optically, and the corresponding axial distributions of radial heat flux were calculated from these temperature distributions.

EQUIPMENT

A photograph of a variable-pitch helical filament mounted in its support structure is shown in figure 1. The support structure and center support rod are molybdenum, and the ceramic seat shown at the bottom of the figure is high-purity aluminum oxide. The filament wire was wound on a grooved fixture as shown in figure 2. In all cases 0.762±0.0005-centimeter tungsten wire was used. After winding, the filament was removed from the grooved fixture and placed over a molybdenum rod, which in turn was placed into a molybdenum setting fixture as shown in figure 3. The pitch of the filament windings was set by inserting pins into the molybdenum setting fixture as shown in figure 4. The setting fixture assembly and filament were then fired in an inert gas furnace at approximately 1400 K for 2 hours in order to stress-relieve the wire. After the inert-gas firing, the filament was projected onto a comparator screen at 20-power magnification, and the winding spacings and overall length were manually readjusted and logged. Reference points from which measurements were made, as well as the winding spacings for a typical filament, are shown in figure 5.

The filament was then positioned in the support structure and fired in a vacuum of 1.33×10^{-4} newton per square meter (1×10^{-6} torr) or better for approximately 8 hours at 2300 K. Following this firing, the winding spacing was again checked on the optical comparator and the final dimensions were recorded.

The filaments were designed to heat a 3.94-centimeter-long section of a hollow 1.33-centimeter-outer-diameter tantalum cylinder with a vapor-deposited rhenium outer surface which simulated the emitter of the thermionic converter described in reference 2. The entire structure is shown schematically in figure 6. The filaments were positioned in the structure so that the uppermost winding was in a 0.157-centimeter-wide region where the emitter and support structure overlapped, and the bottom of the filaments extended to within 0.063 ± 0.008 centimeter of the bottom of the emitter cavity. A photograph of the emitter mounted in a test fixture is presented in figure 7.

Except for the uniformly pitched filament, where the winding spacing was 0.248 ± 0.013 centimeter, the pitch for both the close- and wide-spaced windings was varied from filament to filament in order to retain the same nominal overall filament length.

The total number of full 360° turns in each filament was 16 except in one case for which a 15-turn filament was used. A three-digit coding system was devised in order to facilitate the discussion and to distinguish the various filaments. The first digit denotes the number of close-spaced turns at the top (near the support structure) of the filament, the second digit the number of close-spaced turns at the bottom, and the third digit the total number of turns (a six for 16 turns, and a five for 15). Thus, filament 926 had nine close-spaced turns at the top, two at the bottom, and a total of 16 turns. A table listing important dimensions of each of the six filaments evaluated is presented in table I. The filament and emitter structure were mounted in a vacuum bell jar and when a vacuum of 1.33×10^{-4} newton per square centimeter (1×10^{-6} torr) was achieved, power was applied to the filament.

PROCEDURE

Optical pyrometer brightness temperature was measured axially along the emitter surface at 0.476-centimeter (3/16-in.) intervals. The absolute surface temperature was then calculated from the brightness temperature and the following relation which is derived from Planck's radiation equation (ref. 3):

$$T = \frac{1}{\left(\frac{C_2}{\lambda} \ln \epsilon_\lambda + \frac{1}{S_B}\right)}$$

where

T surface absolute temperature, K

S_B measured surface-brightness temperature, K

ϵ_λ normal spectral emittance of the surface

C_2 second radiation constant, 1.438 cm-K

λ wavelength, cm

As shown in reference 4, at 0.665 micron, which is the nominal wavelength for optical pyrometer temperature measurement, the normal spectral emittance of rhenium is essentially independent of temperature, and a 0.42 emittance was initially used in the absolute temperature calculations. During the test program, axial differences in surface roughness were observed along the emitter surface. At the conclusion of the tests, the following procedure was used to determine the degree to which these surface variations might have affected the normal spectral emittance. Three shallow hohlraums were machined into the emitter surface at three different axial locations as shown in figure 6. Differences in the spectral emittance at the three hohlraum locations were then determined from the hohlraum temperatures and the surface brightness temperatures measured adjacent to each hohlraum location.

Over the temperature range of interest (1778 to 2038 K), the differences in surface temperature due to surface emittance differences were found to be approximately ±10 K. The National Bureau of Standards certified the ribbon filament lamp used in calibration of the optical pyrometer to approximately ±7 K for temperatures up to 2500 K. With the inclusion of a ±3 K observer error (ref. 5), the true surface temperature could, at best, be known only to within approximately ±10 K. Therefore, the effect of variations in spectral emittance due to differences in surface roughness was considered negligible, and a constant spectral emittance of 0.42 was used to correct all surface-brightness temperatures to absolute.

The axial distribution of radial heat flux along the emitter was then calculated from the surface temperature distributions. A one-dimensional heat-transfer analysis was used for these calculations. Rhenium total hemispherical emittance values required for the heat flux calculations were taken from reference 6 and ranged from 0.24 at 1400 K to 0.32 at 2000 K.

RESULTS AND DISCUSSION

The first filament to be examined was a uniformly spaced 16-turn filament designated number 006. The emitter outer-surface temperature distributions, as determined from the measured surface-brightness temperatures, are presented for three mean temperatures in figure 8. Note that the maximum temperature occurs at approximately 3.3 centimeters from the top of the 3.94-centimeter-long emitter. These temperature distributions were used to calculate the corresponding heat flux distributions along the emitter and are presented in figure 9. As shown, heat flux increased from the top of the emitter to the bottom with maximum heat flux differences being on the order of 37 to 53 watts per square centimeter. The reasons for the severe heat losses at the top of the emitter are threefold, namely, conduction along the emitter-support structure, conduction along the filament-support structure, and radiation from the emitter cavity.

In order to compensate for these heat losses, the next test filament was wound with seven close-spaced windings at the top and only three at the bottom (filament number 736). The temperature distributions observed with this filament (fig. 10) were quite similar to those achieved with the uniformly wound filament, with the maximum temperature now occurring at points between 3.1 and 3.25 centimeters from the top of the emitter.

Filament number 726 was then formed in an attempt to decrease the heat flux at the bottom of the emitter and thereby achieve more uniformity. The temperature distributions achieved with this filament (fig. 11) show only a small change in the shape of the temperature distribution relative to the distribution achieved with filament 736; the maximum temperatures now occurred between 2.75 and 3.15 centimeters from the top of the emitter.

In order to further reduce the heat input at the bottom of the emitter the next filament (number 906) was wound with nine close windings at the top and none at the bottom. The temperature distributions achieved with this filament (fig. 12) show that the maximum temperatures now occurred between 0.63 and 0.95 centimeter from the top of the emitter.

The next filament examined, number 925, had a total of 15 turns instead of the usual 16 in an attempt to reduce the heat input to the axial midregion of the emitter by increasing the spacing (pitch) in that area (see table I). These modifications resulted in much flatter temperature distribution curves as indicated in figure 13, but the reduced filament-wire length required 10 to 30 percent more input power, when operated at the same dc voltage as the 16-turn filament, to achieve approximately the same absolute mean surface temperatures as with the 16-turn filaments. This was considered too inefficient a mode of operation, and no further consideration was given to 15-turn filaments.

Filament number 926 was the next evaluated (fig. 14). As shown, maximum temperatures occurred quite close to the midpoint of the emitter and the temperature distribution was nearly symmetrical about the midpoint for each of the three mean temperatures.

The axial distributions of the radial heat flux along the emitter were calculated from the temperature distributions of figure 14 and the results are presented in figure 15. Note that these distributions are also symmetrical about the axial midpoints. The effect of the close-spaced turns at the top of the emitter is apparent when these curves are compared to the uniformly spaced filament heat flux distribution of figure 9.

The fractional changes in axial distribution of radial heat flux are compared in figure 16 for both the uniform filament (number 006) and filament number 926. As a measure of uniformity, the fractional change in heat flux, $(q_h - q_l)/q_l \big|_f$, was determined over fractions of emitter axial length taken symmetrically about the axial midpoint where q_h is the largest heat flux in the particular fraction of axial length f and q_l is the smallest value in the same region.

For example, the heat flux for filament 006 at a mean temperature of 1922 K (fig. 9) and for the central 70 percent of axial length (i.e., 35 percent above (3.35 cm), and 35 percent below (0.59 cm) the axial midpoint) exhibits the following maximum and minimum values:

$$q_h = 58.75 \text{ W/cm}^2$$

$$q_l = 28 \text{ W/cm}^2$$

and

$$\left.\frac{q_h - q_l}{q_l}\right|_{70 \text{ percent}} = 1.10$$

This method for comparing filament performance was used because, in a cesiated cylindrical thermionic converter, the active emitter length (viz., the length which defines the actual emitting area) is somewhat less than the overall emitter length. For example, in the cesiated-converter study conducted with an emitter identical to the one used in this study (ref. 2), the active emitter length was 3.81 centimeters or 96.7 percent of the overall emitter length, and the difference is greater in some designs.

As shown, a significant improvement in emitter axial distributions of heat flux was achieved with the variable-pitch filament. For example, the variations in heat flux for filament number 926 over 85 percent of the axial emitter length is approximately 20 percent, whereas for the uniform-pitch filament (number 006), the heat flux varied axially by a factor of 1.5 (150 percent) over the same length.

The total power input required in the tests discussed herein is several times lower than that required in an operating cesiated thermionic converter. For example, at an emitter-surface mean temperature of approximately 2100 K, the device tested in vacuum required a total power input of 680 watts, whereas a cesiated converter utilizing identical heater and emitter geometries and operating near maximum conversion efficiency required a heat input of approximately 1800 watts in order to achieve the same surface mean temperature (ref. 2). The high heat input for the thermionic converter is due principally to the electron cooling of the emitter and this electron cooling could also affect the heat-flux distribution. However, preliminary evaluation of filament number 926 in a cesiated cylindrical converter (ref. 2) indicated that with proper selection of the dc voltage and ac filament power, heat-flux distributions similar to those achieved in the vacuum tests were realized.

CONCLUDING REMARKS

The results of an evaluation of several helical electron-bombardment filament designs show that when heating a cylindrical thermionic emitting electrode in vacuum, heat losses associated with conduction through the emitter- and filament-support structures as well as thermal radiation from the bottom of the emitter and the cavity into which the heater is inserted can be compensated for by close-packing the turns in the upper and lower sections of the filament. A heat flux, uniform within 20 percent over 85 percent of a 3.94-centimeter emitter length, was achieved with a 16-turn filament having nine close-spaced upper turns and two close-spaced lower turns. This heat-flux distribution was achieved at mean surface temperatures between 1806 and 2038 K.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 29, 1968,
120-27-05-01-22.

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TABLE I. - CHARACTERISTICS OF

FILAMENTS TESTED

Filament number	Average winding spacing, cm		Overall length, cm
	Close	Wide	
006	0.248	0.248	3.92
736	.165	.377	3.82
726	.144	.365	3.85
925	.132	.416	3.78
906	.135	.381	3.77
926	.145	.374	3.79

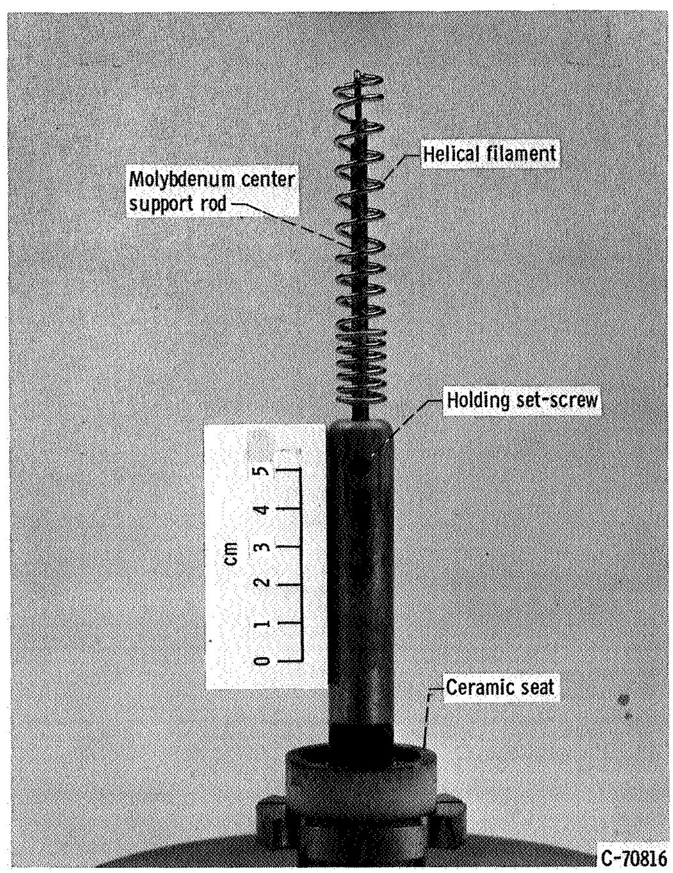


Figure 1. - Helical electron-bombardment filament mounted on molybdenum support structure.

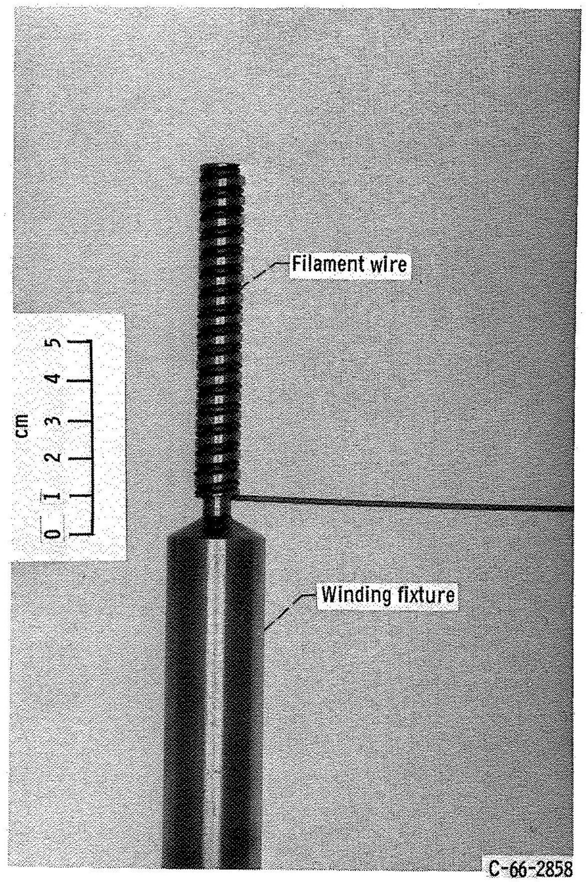


Figure 2. - Helical filament winding fixture showing tungsten wire in place.

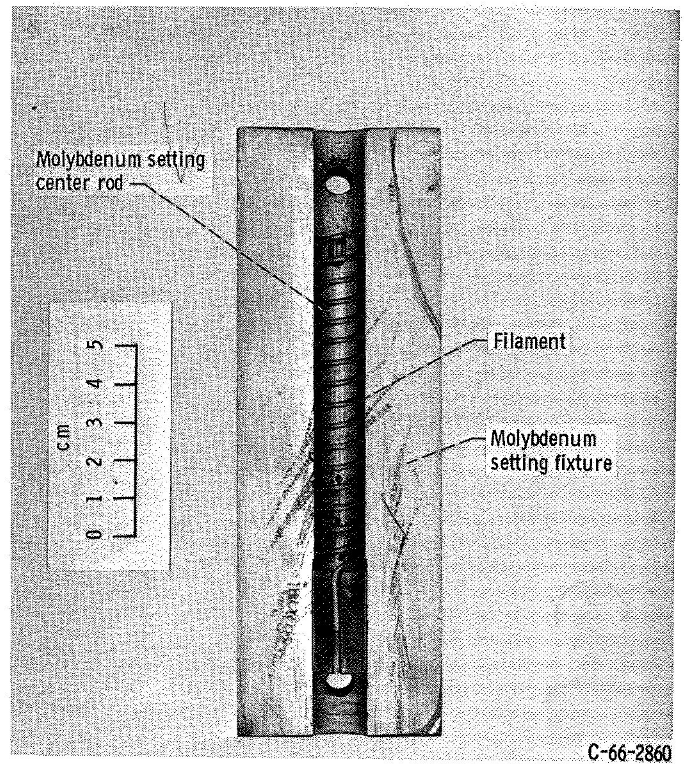


Figure 3. - Molybdenum helical filament setting fixture with filament in place.

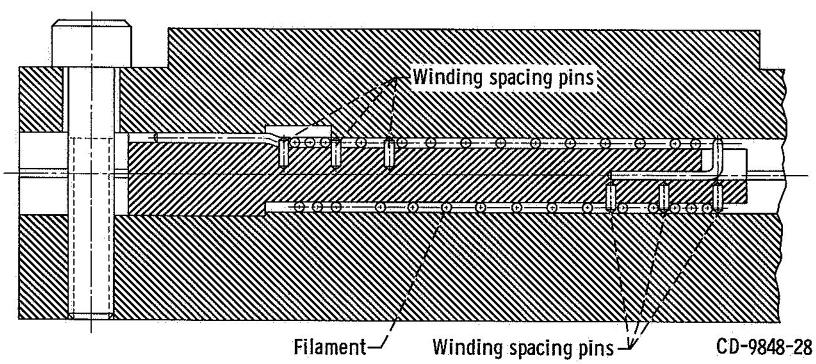
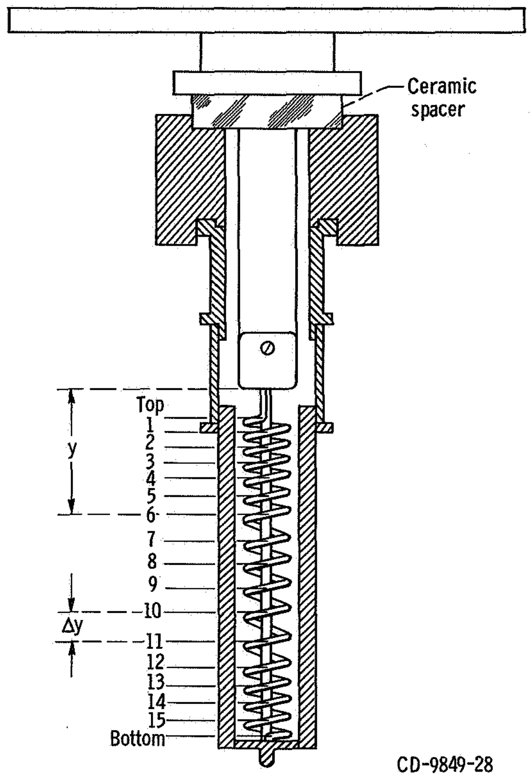


Figure 4. - Cross-sectional view of filament setting fixture showing winding positioning pins.



Turn number	Spacing between filament windings, Δy, cm	Distance from filament support to each winding, y, cm	Turn number	Spacing between filament windings, Δy, cm	Distance from filament support to each winding, y, cm
Top	-----	-----	9	0.243	2.231
1	0.249	0.249	10	.248	2.479
2	.250	.499	11	.247	2.726
3	.235	.734	12	.250	2.976
4	.244	.978	13	.245	3.221
5	.252	1.230	14	.251	3.472
6	.250	1.480	15	.244	3.716
7	.248	1.728	Bottom	.249	3.965
8	.260	1.988	--	-----	3.974

Figure 5. - Cross-sectional view of emitter and support structure with mounted filament and winding layout form for typical filament.

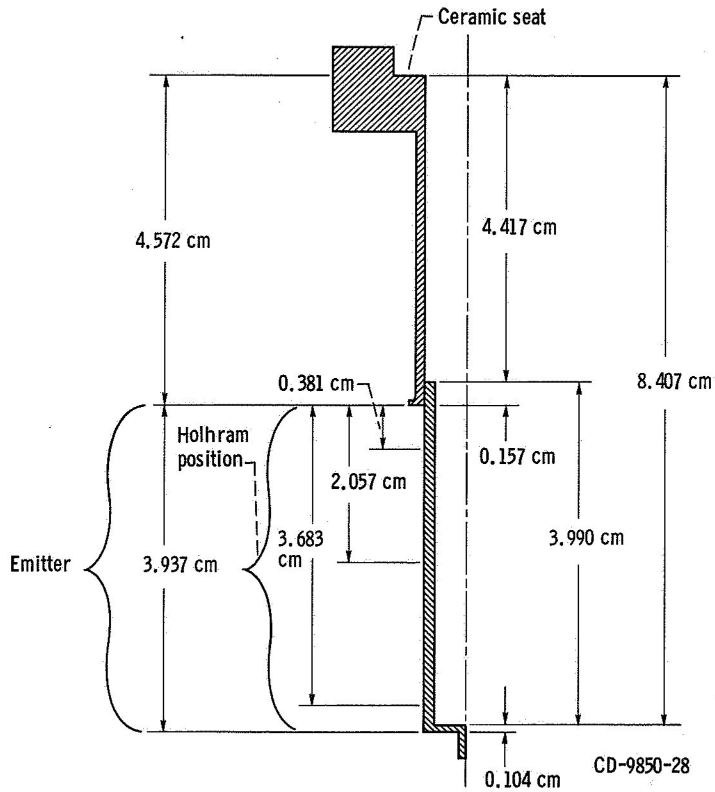


Figure 6. - Schematic diagram of emitter and support structure showing blackbody hohlraum positions.

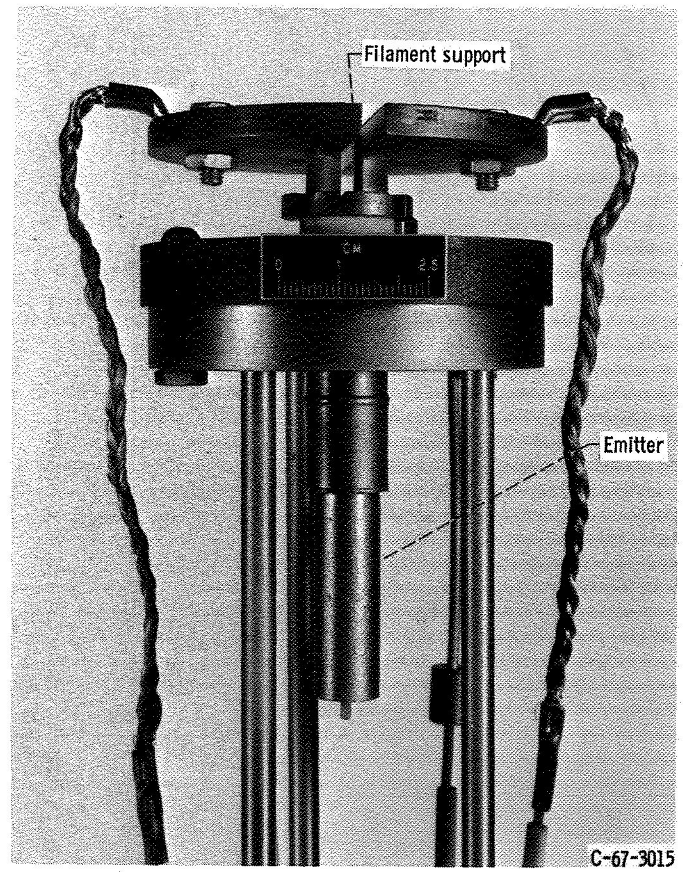


Figure 7. - Simulated thermionic emitter assembly in support fixture.

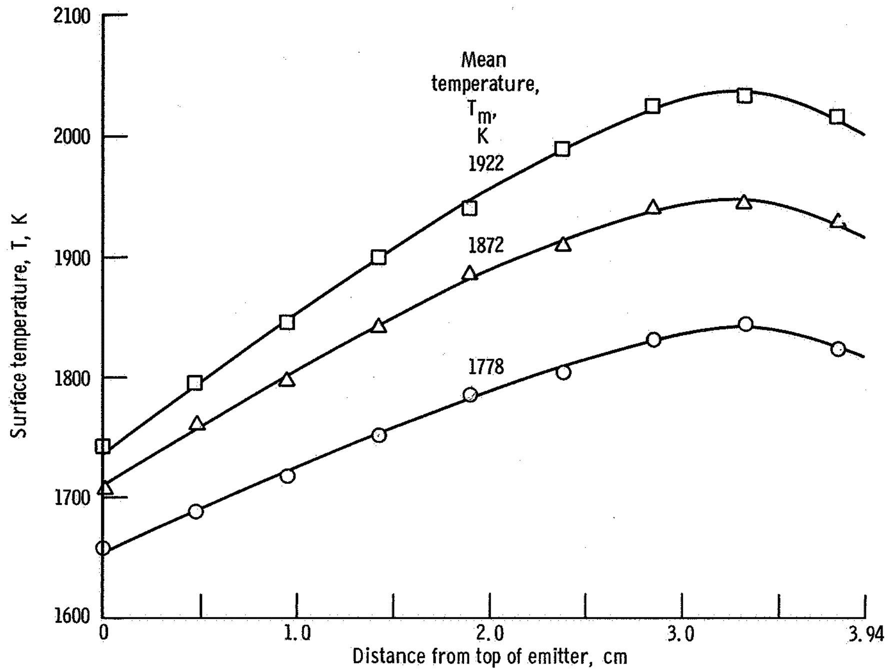


Figure 8. - Emitter outer-surface temperature distributions for uniformly spaced winding filament (number 006).

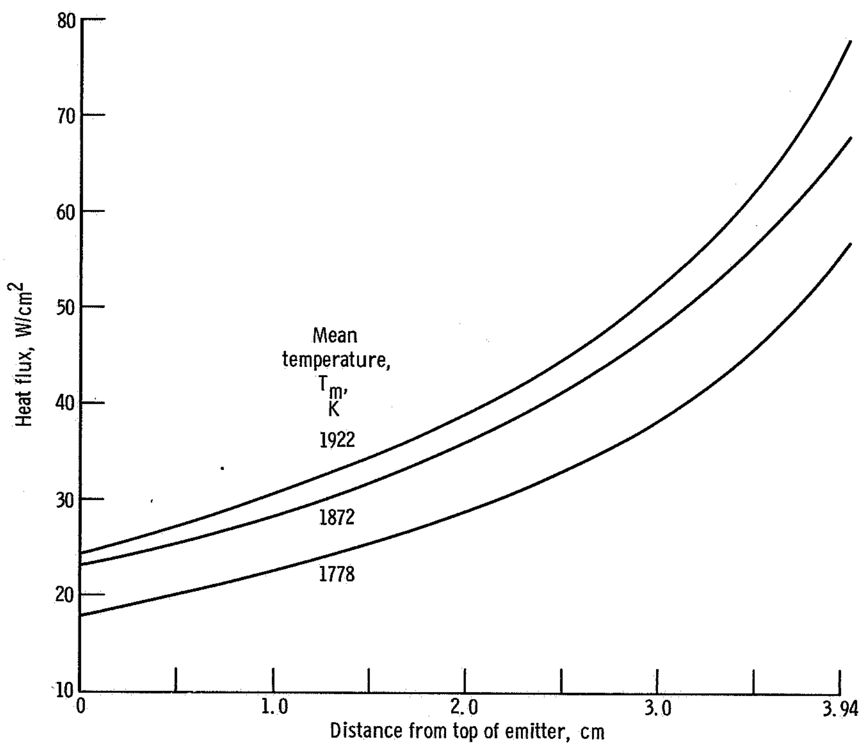


Figure 9. - Calculated heat flux distribution along emitter resulting from use of uniformly pitched helical filament (number 006).

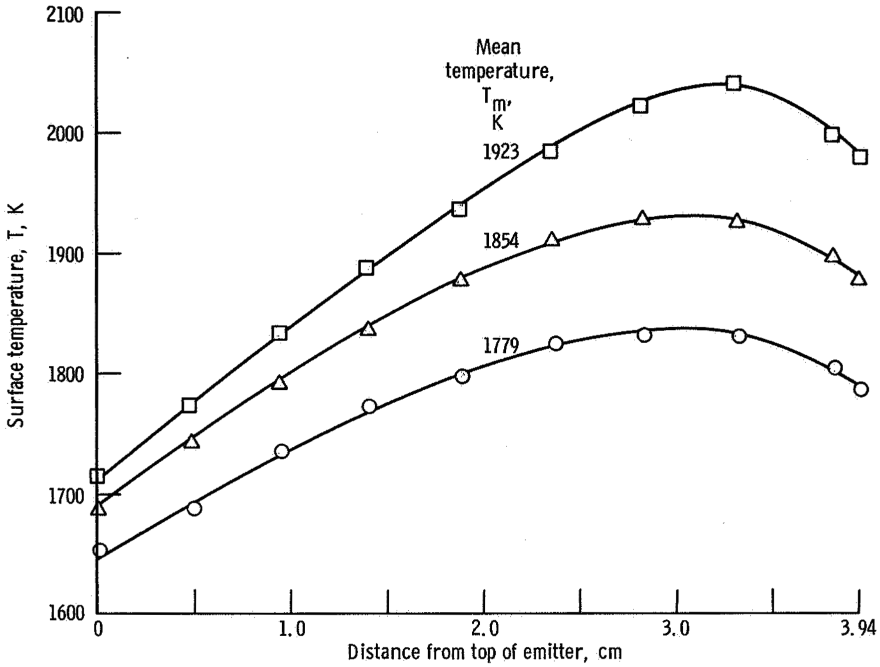


Figure 10. - Surface temperature distributions for filament number 736.

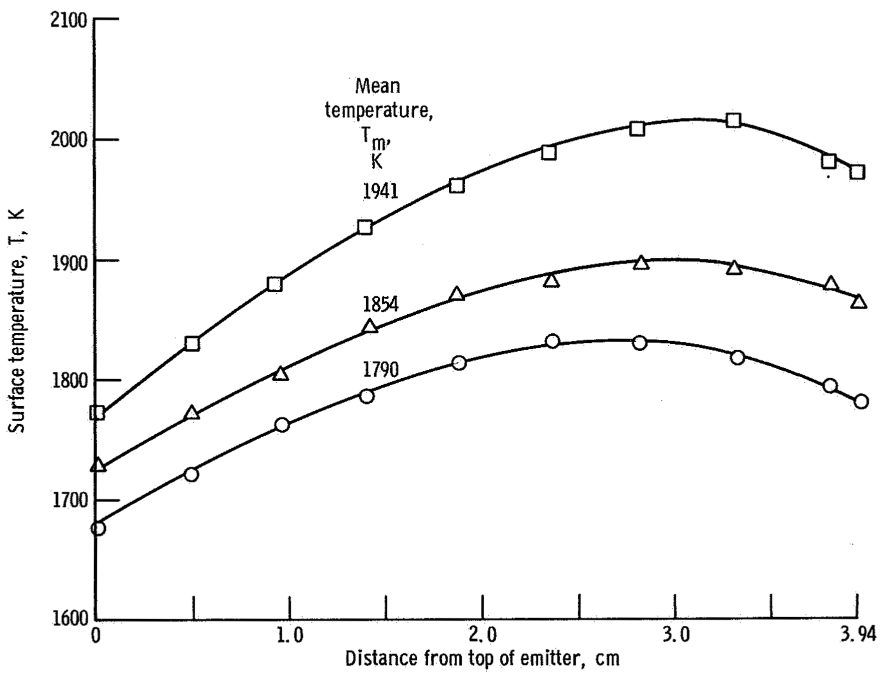


Figure 11. - Surface temperature distributions for filament number 726.

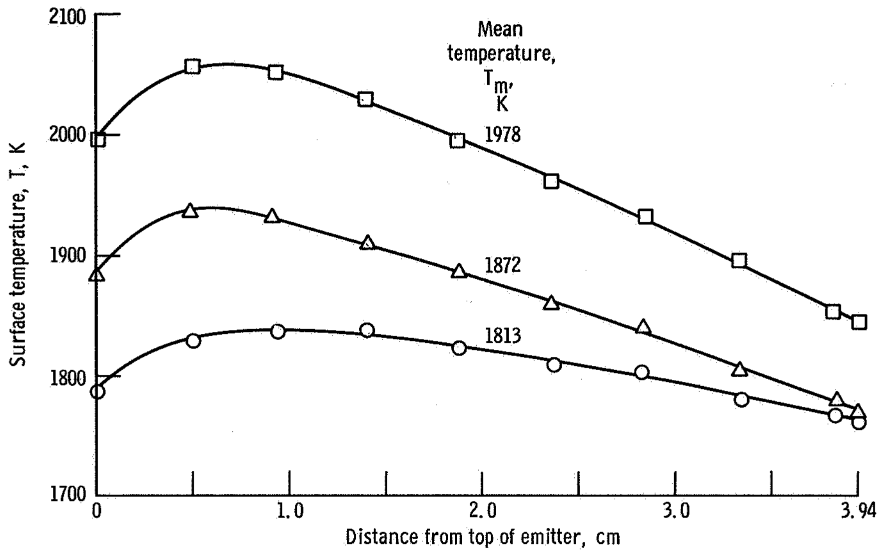


Figure 12. - Surface temperature distributions for filament number 906.

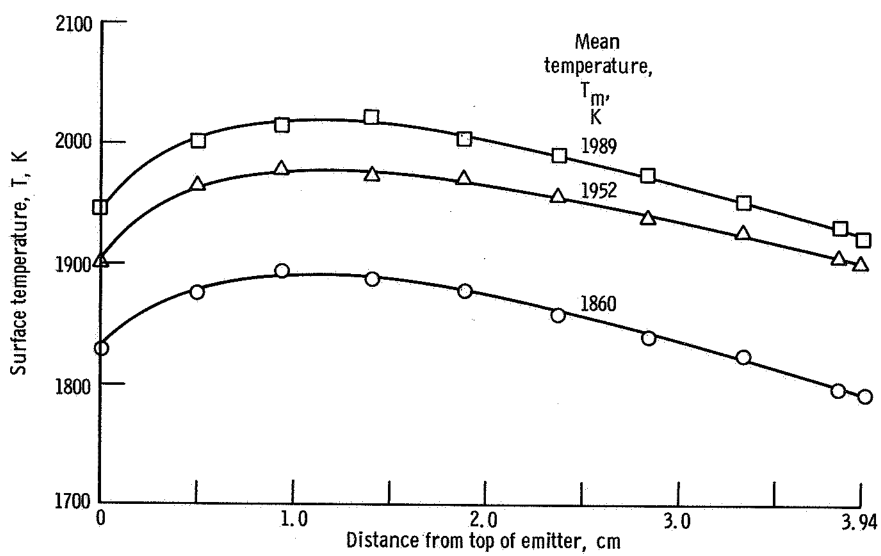


Figure 13. - Surface temperature distributions for filament number 925.

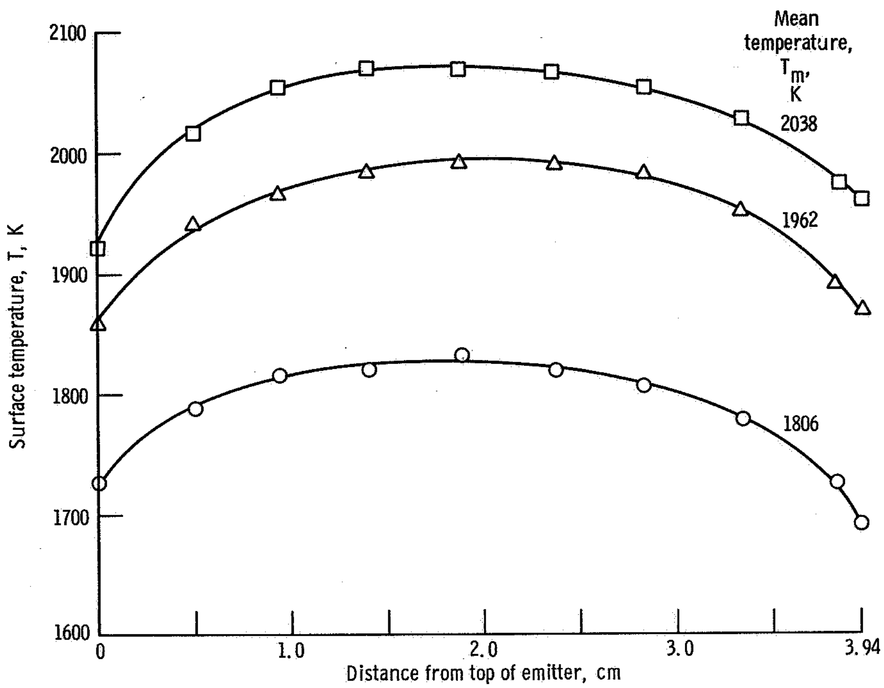


Figure 14. - Surface temperature distributions for filament number 926.

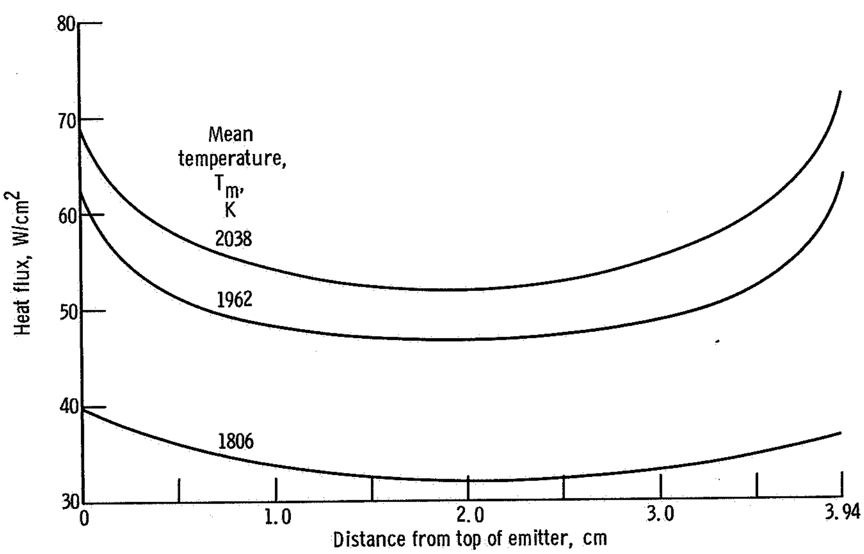


Figure 15. - Calculated heat flux distribution along emitter resulting from use of filament number 926.

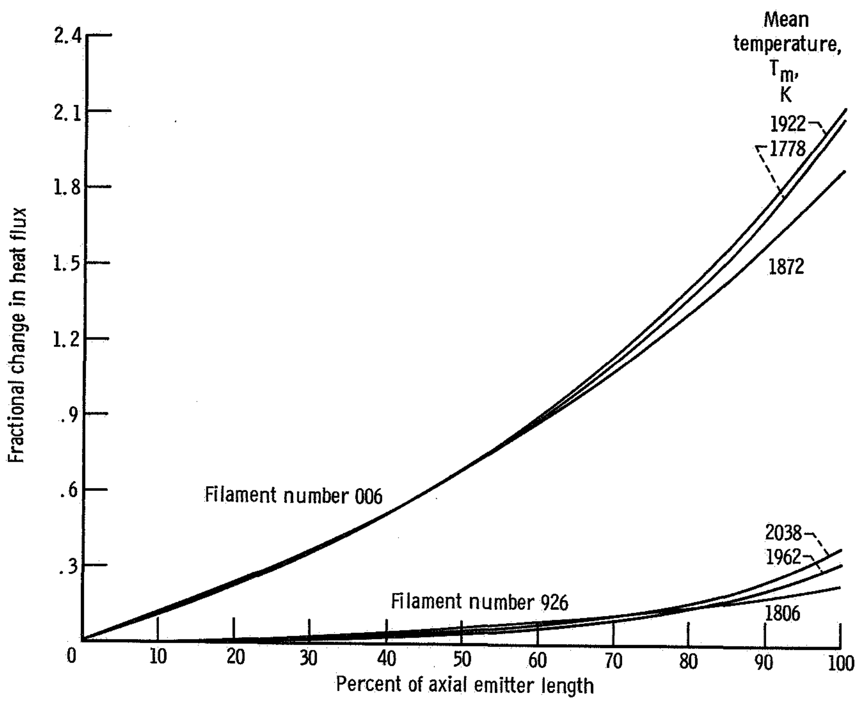


Figure 16. - Comparison of fractional changes in emitter heat flux for filaments number 006 and number 926.

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