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by James F. Morris

Lewis Research Center

Cleveland, Ohio

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SUMMARY

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Theoretic evaluations of heat transfer caused by electron emission opposed by a barrier that terminates at the Fermi level on the emitter surface are presented. For these predictions, electric fields vary from 10^6 to 10^8 volts per centimeter, work functions range from 1 to 8 volts, and emitter temperatures span from 0° to 3000° K. Current density and cooling voltage show graphically the trends of emitter cooling (cooling rate equals current density times cooling voltage); in addition, values of cooling rate, current density, and cooling voltage appear in tables. Because true transport rates for thermal field emission probably exceed these estimates (up to 10^9 W/cm^2), high fields provide powerful processes for heating and cooling.

Author

INTRODUCTION

Changes in electron emission shift emitter temperatures. But this heat transfer hardly affects electron tubes with low power intensities; thus it required and received little attention until recently. Now, however, the growing use of high current densities in electronics compels recognition of energy transport by thermal field emission. In response, this report submits computed cooling and heating rates caused by the escape of electrons over and through a potential barrier that terminates at the Fermi level on the emitter surface (TIP, refs. 1 and 2).

Temperature trends of an emitter depend on which of its energy levels loses many electrons. In thermionics, each exodic electron surrenders enough kinetic energy to clear a confining barrier that rises well above the Fermi level. During pure field emission (0° K), though, electrons tunnel through the potential wall below the Fermi level. If conducting electrons move from near the Fermi level (ref. 3) to replace their departed counterparts, the emitter cools with thermionic emission and heats with field emission; this mechanism is assumed in the present analysis.

Recent studies (refs. 4 and 5) verify the heating effect of field emission, but questions arise when experiments confront a theory that assumes a flat emitter, a simple image potential, and no penetration by external fields (ref. 5). That such a model predicts numbers even near emission results for 5×10^7 volts per centimeter (ref. 4) is gratifying; this intensity equals the permanent surface fields of the emitter and reduces the thickness of the potential barrier to atomic dimensions. Tests of existing theories at 5×10^6 volts per centimeter seem more rational. Nonetheless, emission heating and cooling occur and, when electronic conduction prevails, probably result from replacement of emitted electrons by ones close to the Fermi level.

To indicate this phenomenon, this report tabulates computed energy flows for emission with fields from 10^6 to 10^8 volts per centimeter, emitter temperatures from 0° to 3000° K, and work functions from 1 to 8 volts. These heating and cooling rates come from a simple combination of some average properties for TIP thermal field emission calculated initially for reference 2. Current densities, also taken from that work, appear here with their corresponding heat-transfer rates. When the power loss caused by emission is divided by the emitter current, the quotient is a cooling voltage. Plots of cooling voltage and log of current density against work function with temperature as a parameter for each electric field used in the calculations show the trends of transport by thermal field emission.

References 1 and 2 detail the limitations and applicability of thermal field emission with a terminated image potential. In general, however, these results do not apply where simple image potentials and the free-electron theory fail.

THEORY

Emitter cooling by thermal field emission ΔQ_c is the difference in the energy flows of the escaping electrons $\left(Q_e = nm\langle v^3\rangle/2\right)$ and their replacement current $\left(Q_r = n\langle v\rangle\mu\right)$:

$$\Delta Q_c = n\left(\frac{m}{2}\langle v^3\rangle - \langle v\rangle\mu\right) \tag{1}$$

The number density n, mass m, and velocity v characterize the electrons within the emitter that are about to escape. Values of n, $m\langle v^3\rangle/2$, and $\langle v\rangle$ for the present calculations came from the work for reference 2, which contains properties for TIP thermal field emission as functions of electric field E and emitter temperature T, work function φ, and Fermi level μ.

These variables appear in the integral form for energy transport by electron emission

$$\Delta Q_c = n \frac{m}{2} \langle v^3 \rangle - n\mu \langle v \rangle$$

$$= \frac{m}{2} \int_0^\infty P(\mu, \varphi, E, v_x) N(\mu, T, v_x) v_x v^2(\mu, T, v_x) dv_x - \mu \int_0^\infty P(\mu, \varphi, E, v_x) N(\mu, T, v_x) v_x \, dv_x$$

$$= \int_0^\infty P(\mu, \varphi, E, v_x) N(\mu, T, v_x) \left[\frac{m}{2} v^2(\mu, T, v_x) - \mu\right] v_x \, dv_x,$$

which becomes, after changing variables,

$$\int_{-\mu}^\infty P(\varphi, E, \epsilon_x - \mu) f(T, \epsilon_x - \mu) \left[\epsilon_{yz}(T, \epsilon_x - \mu) + \epsilon_x - \mu\right] d(\epsilon_x - \mu) = \Delta Q_c(\mu, \varphi, E, T) \tag{2}$$

Here ϵ_x and ϵ_{yz} are kinetic energies based on those velocity components perpendicular (v_x) to and parallel (v_{yz}) with the emitter surface, P is the penetration probability, and N and f are equal and describe the velocity distribution of electrons moving in the x-direction within the emitter.

With the factor in the square brackets removed, equation (2) resembles the expression for emitter current density (ref. 2, eq. (5)). And the parallel continues because the energy and charge flows of thermal field emission depend similarly on the chemical potential of the emitter.

Fermi levels for conventional emitters influence the heat transfer and current density of emission only at fields above $10^{7.5}$ volts per centimeter (ref. 2). Otherwise, as $\epsilon_x \to 0$, the penetration probability reduces tunneling to negligibility before the electron supply function cuts off emission at $\epsilon_x = 0$. This allows integration of equation (2) between $-\infty$ and ∞ rather than $-\mu$ and ∞:

$$\Delta Q_c \approx \int_\infty^\infty P(\varphi, E, \epsilon_x - \mu) f(T, \epsilon_x - \mu) \left[\epsilon_{yz}(T, \epsilon_x - \mu) + \epsilon_x - \mu\right] d(\epsilon_x - \mu) = \Delta Q_c(\varphi, E, T) \tag{3}$$

The change in integration limits causes negligible error except at low Fermi levels and very high fields, where emission models based on simple image potentials fail in any event.

DISCUSSION OF RESULTS

Figures 1 to 5 (and table I) show theoretic effects of variables of thermal, field emission on emitter cooling and heating. For these findings, emitter temperatures range from 0^{o} to 3000^{o} K, work functions from 1 to 8 volts, and fields from 10^{6} to 10^{8} volts per centimeter. In figures 1 to 5, current density J and cooling voltage ΔV_c indicate emitter cooling $\Delta Q_c = J\ \Delta V_c$; J runs from 10^{10} to 10^{-30} ampere per square centimeter, while ΔV_c falls between -0.6 and 9 volts. These plots follow patterns: Where field emission dominates, the ΔV_c curves bend toward the horizontal and separate widely with the temperature variation as they rise with increasing φ. But the lines for log J as a function of φ incline toward the vertical and group closely over the temperature range as they decline. When thermionic emission prevails, the ΔV_c graphs approach a unit tangent and cluster tightly for large temperature increments. The log J curves, however, tend toward downward sloping straight lines ($d \log J/d\varphi \rightarrow -e/\kappa T$) and spread apart with temperature changes.

Relatively, as φ increases, J drops rapidly (nearly exponentially) while ΔV_c climbs slowly (ultimately linearly). Therefore, emitter cooling (or heating) follows the emission current except in the region where ΔV_c passes through zero.

These results suffer the constraints of the TIP model for thermal field emission, which was tied down rather firmly in references 1 and 2. In general, theories for electron escape opposed only by image potentials perform well at fields below 10^{7} volts per centimeter. For most conditions, however, real emitters should yield greater currents and probably more energy transport than this work predicts (ref. 2). But even here, at 10^{8} volts per centimeter with φ ranging from 6 to 2 (conventional emitters), emission heating rates range from 10^{5} to 10^{9} watts per square centimeter.

If, as it appears, these energy flows for thermal field emission underrate reality, high fields should become effective tools of thermal engineering.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 28, 1966.

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TABLE I. - EMITTER COOLING FOR TIP THERMAL FIELD EMISSION

(a) Electrostatic field, E, 10^8 volts per centimeter

Emitter temperature, T, $^\circ$K		Work function, φ, V			
		2	4	6	8
3000	Cooling rate, ΔQ_c, W/cm^2	-1.62×10^{9}	8.42×10^{7}	2.54×10^{6}	1.97×10^{4}
	Current density, J, A/cm^2	7.06×10^{9}	4.15×10^{8}	5.00×10^{6}	2.45×10^{4}
	Cooling voltage, ΔV_c, V	-0.229	0.203	0.508	0.804
2000	Cooling rate, ΔQ_c, W/cm^2	-2.38×10^{9}	-4.03×10^{7}	-8.81×10^{4}	6.42×10^{2}
	Current density, J, A/cm^2	6.26×10^{9}	2.84×10^{8}	2.77×10^{6}	1.09×10^{4}
	Cooling voltage, ΔV_c, V	-0.380	-0.142	-0.0318	0.0589
1000	Cooling rate, ΔQ_c, W/cm^2	-2.79×10^{9}	-7.72×10^{7}	-5.63×10^{5}	-1.70×10^{3}
	Current density, J, A/cm^2	5.75×10^{9}	2.26×10^{3}	2.02×10^{6}	7.29×10^{3}
	Cooling voltage, ΔV_c, V	-0.485	-0.342	-0.279	-0.233
300	Cooling rate, ΔQ_c, W/cm^2	-2.90×10^{9}	-8.39×10^{7}	-6.34×10^{5}	-2.00×10^{3}
	Current density, J, A/cm^2	5.58×10^{9}	2.11×10^{8}	1.85×10^{6}	6.52×10^{3}
	Cooling voltage, ΔV_c, V	-0.520	-0.398	-0.342	-0.307
0	Cooling rate, ΔQ_c, W/cm^2	-2.91×10^{9}	-8.45×10^{7}	-6.40×10^{5}	-2.00×10^{3}
	Current density, J, A/cm^2	5.57×10^{9}	2.11×10^{6}	1.84×10^{6}	6.48×10^{3}
	Cooling voltage, ΔV_c, V	-0.528	-0.400	-0.348	-0.309

(b) Electrostatic field, E, $10^{7.5}$ volts per centimeter

Emitter temperature, T, $^\circ$K		Work function, φ, V			
		2	4	6	8
3000	Cooling rate, ΔQ_c, W/cm^2	3.03×10^{8}	1.79×10^{6}	2.13×10^{3}	1.65×10^{0}
	Current density, J, A/cm^2	4.81×10^{8}	8.24×10^{5}	5.22×10^{2}	2.74×10^{-1}
	Cooling voltage, ΔV_c, V	0.630	2.17	4.08	6.02
2000	Cooling rate, ΔQ_c, W/cm^2	6.58×10^{7}	3.44×10^{4}	1.34×10^{0}	2.60×10^{-5}
	Current density, J, A/cm^2	1.98×10^{8}	2.42×10^{4}	4.23×10^{-1}	5.09×10^{-6}
	Cooling voltage, ΔV_c, V	0.332	1.42	3.17	5.11
1000	Cooling rate, ΔQ_c, W/cm^2	-2.25×10^{6}	9.69×10^{1}	1.05×10^{-4}	6.95×10^{-12}
	Current density, J, A/cm^2	7.49×10^{7}	1.13×10^{3}	5.38×10^{-4}	2.05×10^{-11}
	Cooling voltage, ΔV_c, V	-0.0300	0.0856	0.195	0.339
300	Cooling rate, ΔQ_c, W/cm^2	-8.84×10^{6}	-7.44×10^{1}	-2.06×10^{-5}	-4.35×10^{-13}
	Current density, J, A/cm^2	5.26×10^{7}	6.01×10^{2}	2.07×10^{-4}	5.26×10^{-12}
	Cooling voltage, ΔV_c, V	-0.168	-0.124	-0.0995	-0.0826
0	Cooling rate, ΔQ_c, W/cm^2	-9.17×10^{6}	-7.94×10^{1}	-2.27×10^{-5}	-4.97×10^{-13}
	Current density, J, A/cm^2	5.15×10^{7}	5.79×10^{2}	1.97×10^{-4}	4.90×10^{-12}
	Cooling voltage, ΔV_c, V	-0.178	-0.137	-0.115	-0.102

TABLE I. - Concluded. EMITTER COOLING FOR TIP THERMAL FIELD EMISSION

(c) Electrostatic field, E, 10^{7} volts per centimeter

Emitter temperature, T, ^{o}K		Work function, φ, V					
		2	3	4	5	6	8
3000	Cooling rate, ΔQ_c, W/cm^2	4.76×10^{7}	2.12×10^{6}	7.04×10^{4}	2.05×10^{3}	5.52×10^{1}	3.52×10^{-2}
	Current density, J, A/cm^2	3.42×10^{7}	9.09×10^{5}	2.13×10^{4}	4.78×10^{2}	1.05×10^{1}	4.85×10^{-3}
	Cooling voltage, ΔV_c, V	1.39	2.33	3.30	4.29	5.26	7.26
2000	Cooling rate, ΔQ_c, W/cm^2	3.45×10^{6}	2.65×10^{4}	1.39×10^{2}	6.13×10^{-1}	2.46×10^{-3}	3.42×10^{-8}
	Current density, J, A/cm^2	2.90×10^{6}	1.25×10^{4}	4.47×10^{1}	1.50×10^{-1}	4.87×10^{-4}	4.84×10^{-9}
	Cooling voltage, ΔV_c, V	1.19	2.12	3.11	4.09	5.05	7.06
1000	Cooling rate, ΔQ_c, W/cm^2	7.01×10^{3}	2.81×10^{-1}	5.67×10^{-6}	----------	1.16×10^{-15}	1.64×10^{-25}
	Current density, J, A/cm^2	8.68×10^{3}	1.63×10^{-1}	2.11×10^{-6}	----------	2.49×10^{-16}	2.46×10^{-26}
	Cooling voltage, ΔV_c, V	0.808	1.72	2.69	----------	4.66	6.66
300	Cooling rate, ΔQ_c, W/cm^2	-1.74×10^{0}	-2.29×10^{-8}	2.39×10^{-16}	1.66×10^{-25}	----------	----------
	Current density, J, A/cm^2	7.48×10^{1}	5.31×10^{6}	1.96×10^{-14}	5.92×10^{-24}	----------	----------
	Cooling voltage, ΔV_c, V	-0.0232	-0.00431	0.0122	0.0280	----------	----------
0	Cooling rate, ΔQ_c, W/cm^2	-3.52×10^{0}	-1.90×10^{-7}	-5.50×10^{-16}	-1.32×10^{-25}	----------	----------
	Current density, J, A/cm^2	6.04×10^{1}	3.87×10^{-6}	1.27×10^{-14}	3.34×10^{-24}	----------	----------
	Cooling voltage, ΔV_c, V	-0.0584	-0.0504	-0.0433	-0.0395	----------	----------

(d) Electrostatic field, E, $10^{6.5}$ volts per centimeter

Emitter temperature, T, ^{o}K		Work function, φ, V					
		1	2	3	4	6	8
3000	Cooling rate, ΔQ_c, W/cm^2	1.99×10^{8}	1.07×10^{7}	3.71×10^{5}	1.08×10^{4}	7.47×10^{0}	4.46×10^{-3}
	Current density, J, A/cm^2	2.12×10^{8}	5.74×10^{6}	1.30×10^{5}	2.83×10^{3}	1.28×10^{0}	5.70×10^{-4}
	Cooling voltage, ΔV_c, V	0.939	1.86	2.86	3.82	5.84	7.83
2000	Cooling rate, ΔQ_c, W/cm^2	3.32×10^{7}	3.18×10^{5}	1.71×10^{3}	7.49×10^{0}	1.12×10^{-4}	1.41×10^{-9}
	Current density, J, A/cm^2	4.42×10^{7}	1.88×10^{5}	6.39×10^{2}	2.05×10^{0}	1.97×10^{-5}	1.85×10^{-10}
	Cooling voltage, ΔV_c, V	0.750	1.69	2.68	3.65	5.68	7.62
1000	Cooling rate, ΔQ_c, W/cm^2	6.33×10^{5}	2.96×10^{1}	----------	8.04×10^{-9}	1.18×10^{-18}	1.37×10^{-28}
	Current density, J, A/cm^2	1.13×10^{6}	1.97×10^{1}	----------	2.31×10^{-9}	2.15×10^{-19}	1.83×10^{-29}
	Cooling voltage, ΔV_c, V	0.560	1.50	----------	3.48	5.49	7.49
300	Cooling rate, ΔQ_c, W/cm^2	7.50×10^{0}	2.10×10^{-14}	1.57×10^{-30}	---------	----------	----------
	Current density, J, A/cm^2	5.08×10^{1}	2.75×10^{-14}	9.03×10^{-31}	---------	----------	----------
	Cooling voltage, ΔV_c, V	0.148	0.764	1.74	---------	----------	----------
0	Cooling rate, ΔQ_c, W/cm^2	-1.79×10^{-1}	-4.22×10^{-19}	----------	---------	----------	----------
	Current density, J, A/cm^2	6.53×10^{0}	2.15×10^{-17}	----------	---------	----------	----------
	Cooling voltage, ΔV_c, V	-0.0274	-0.0196	----------	---------	----------	----------

(e) Electrostatic field, E, 10^{6} volts per centimeter

Emitter temperature, T, ^{o}K		Work function, φ, V					
		1	2	3	4	6	8
3000	Cooling rate, ΔQ_c, W/cm^2	1.01×10^{8}	4.25×10^{6}	1.33×10^{5}	3.72×10^{3}	2.43×10^{0}	1.42×10^{-3}
	Current density, J, A/cm^2	8.60×10^{7}	1.98×10^{6}	4.25×10^{4}	8.98×10^{2}	3.97×10^{-1}	1.74×10^{-4}
	Cooling voltage, ΔV_c, V	1.17	2.14	3.13	4.15	6.12	8.15
2000	Cooling rate, ΔQ_c, W/cm^2	1.10×10^{7}	7.44×10^{4}	3.51×10^{2}	1.44×10^{0}	2.01×10^{-5}	2.47×10^{-10}
	Current density, J, A/cm^2	1.10×10^{7}	3.77×10^{4}	1.18×10^{2}	3.63×10^{-1}	3.37×10^{-6}	3.10×10^{-11}
	Cooling voltage, ΔV_c, V	1.00	1.97	2.98	3.97	5.96	7.96
1000	Cooling rate, ΔQ_c, W/cm^2	5.26×10^{4}	1.33×10^{0}	2.02×10^{-5}	2.59×10^{-10}	3.40×10^{-20}	----------
	Current density, J, A/cm^2	6.42×10^{4}	7.37×10^{-1}	7.23×10^{-6}	6.83×10^{-11}	5.88×10^{-21}	----------
	Cooling voltage, ΔV_c, V	0.820	1.80	2.80	3.80	5.79	----------
300	Cooling rate, ΔQ_c, W/cm^2	1.23×10^{-4}	9.46×10^{-21}	---------	----------	----------	----------
	Current density, J, A/cm^2	1.82×10^{-4}	5.69×10^{-21}	---------	----------	----------	----------
	Cooling voltage, ΔV_c, V	0.676	1.66	---------	----------	----------	----------
0	Cooling rate, ΔQ_c, W/cm^2	-3.25×10^{-22}	----------	---------	----------	----------	----------
	Current density, J, A/cm^2	3.66×10^{-20}	----------	---------	----------	----------	----------
	Cooling voltage, ΔV_c, V	-0.00888	----------	---------	----------	----------	----------

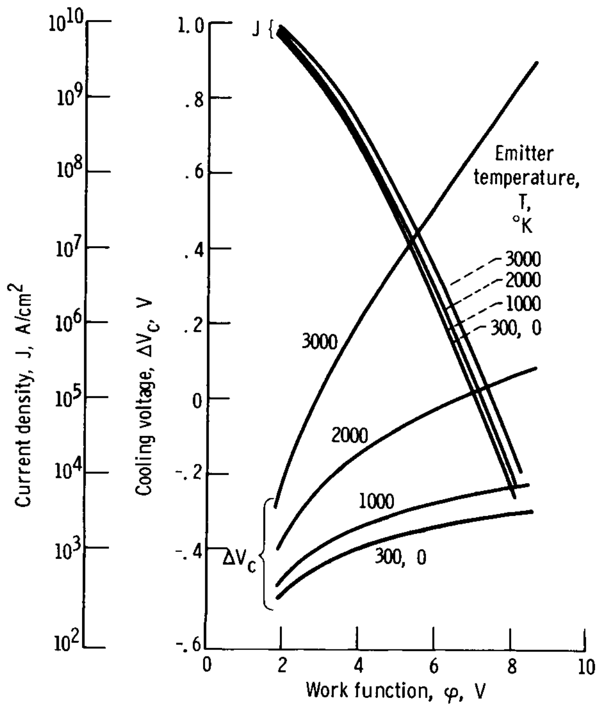

Figure 1. - Emitter cooling for 10^8 volts per centimeter. $\Delta Q_c = J\Delta V_c$.

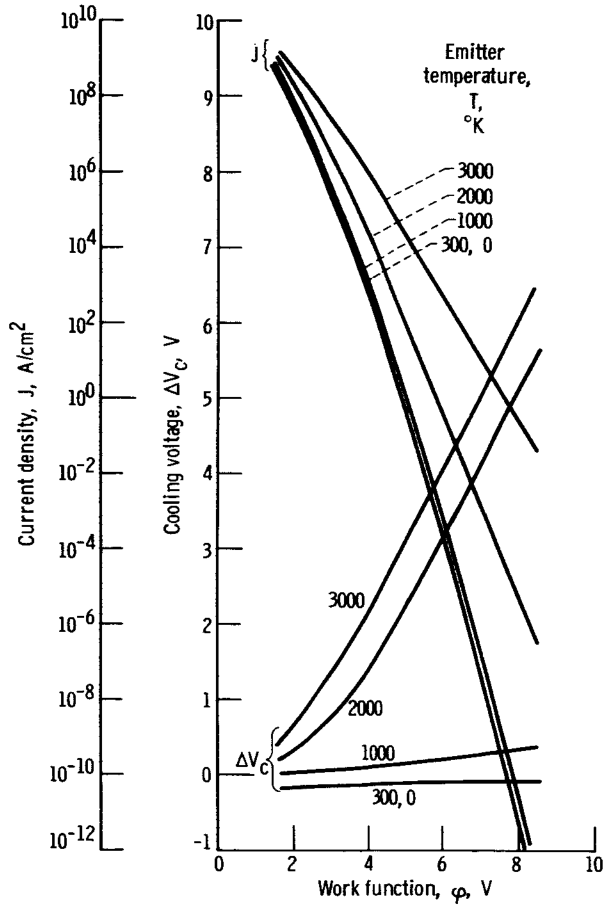

Figure 2. - Emitter cooling for $10^{7.5}$ volts per centimeter. $\Delta Q_c = J\Delta V_c$.

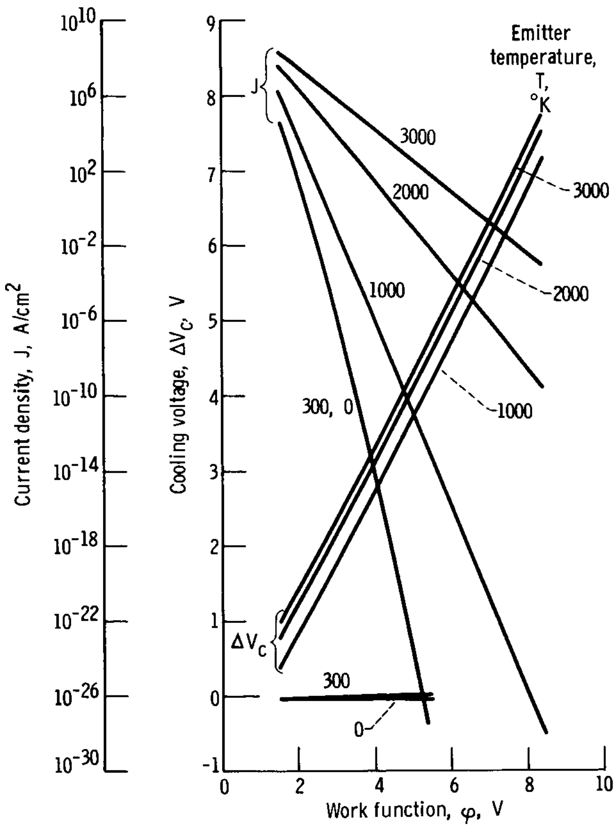

Figure 3. - Emitter cooling for 10^7 volts per centimeter. $\Delta Q_C = J \Delta V_C$.

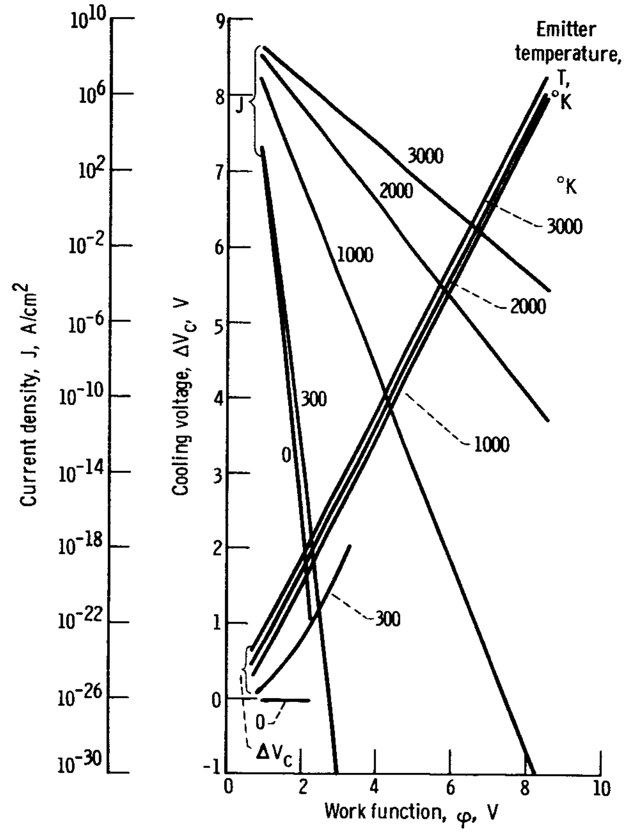

Figure 4. - Emitter cooling for $10^{6.5}$ volts per centimeter. $\Delta Q_c = J \Delta V_c$.

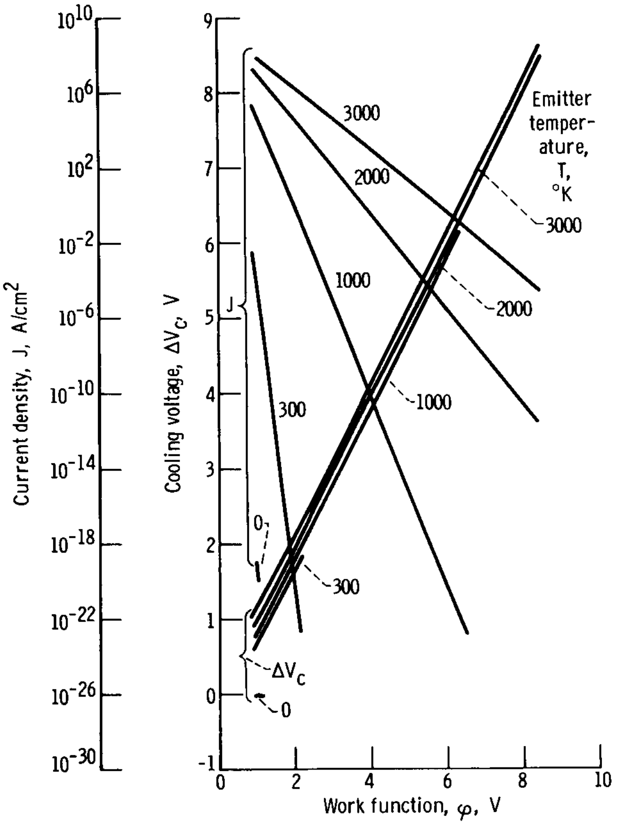

Figure 5. - Emitter cooling for 10^6 volts per centimeter. $\Delta Q_c = J\Delta V_c$.

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