DISPENSER CATHODE LIFE PREDICTION MODEL

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ABSTRACT

A dispenser cathode life prediction model is presented that provides a method of calculating how the cathode current changes with time and temperature. Both the tungsten dispenser cathode and the metal coated dispenser cathode are considered. The model is compared to accelerated life test data taken in TWT type guns for tungsten dispenser B-type and for the osmium-ruthenium dispenser M-type cathodes.

INTRODUCTION

The development of a Dispenser Cathode life prediction model from first principles requires a thorough understanding of the physics and chemistry of the cathodes. This complete knowledge is not yet available. From an engineering point of view we cannot wait for a complete picture, but most proceed in an empirical way, modeling with the best information and refining model as information becomes available.

The purpose for constructing this model was to aid in the engineering and manufacture of TWTs. The empirical model serves another purpose; it sets down some ideas that can be tested as new data becomes available.

CATHODE CURRENT DENSITY VERSUS TIME

The problem of developing a life prediction model reduces to one of describing how the cathode current density changes with time. In the past the general consensus was that a cathode does not degrade while space charge limited and then suddenly decrease when it becomes temperature limited. This behavior has never been observed. In fact, there seems to be a slow continuous change from space charge to temperature limited emission. The rate of this change depends on the temperature of the cathode.

To proceed with a life prediction model we must provide some means of calculating the total cathode current density as a function of cathode characteristics such as work function. The total current must provide reasonable results over the entire operating range of voltage and temperature.

In this effort we rely upon an empirical relationship, which we have found experimentally to be a reasonable good representation of the observed current at any voltage or temperature. The empirical relationship is

$$1/J = 1/J_{SC} + 1/J_{TL} \tag{1}$$

where

$$J_{SC} = 2.33 \times 10^{-6} V^{3/2}/d^2 \tag{2}$$

and

$$J_{TL} = AT^2 e^{-11600\phi(t)/T} e^{4.4\sqrt{V/d}/T}. \tag{3}$$

The entire time dependence is assumed to enter through the work function $\phi(t)$.

An earlier attempt to model the life of dispenser cathodes(1) assumed the work function did not explicitly depend on time but depended on a surface coverage factor $\theta(t)$ which contained all of the time dependence. This model take the same approach but develops a more realistic function $\phi(\theta)$.

SURFACE COVERAGE WORKFUNCTION MODEL

This model describes the spatial averaged work-function $\bar{\phi}$ as a function of the fractional coverage θ. The surface is expected to be patchy on a small scale (i.e. there are areas with no coverage; areas with one monolayer and areas with two or more monolayers). Figure 1 shows schematically what the surface look like at some value of θ if these areas are gathered together. The total area with metal substrate exposed is A_M. The area with one monolayer is A_{ML} and A_{Ba} is the area with

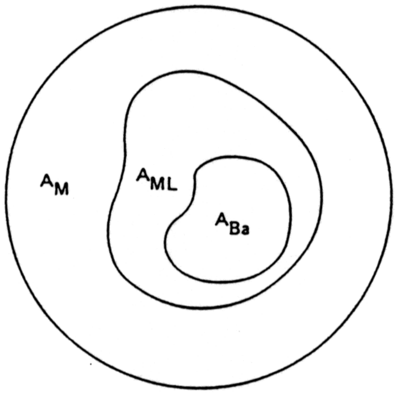

Figure 1 A schematic representation of the accumulated areas at some value of θ.

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two or more monolayer. It is assumed that the spatial average can be described by

$$\bar{\phi}(\theta) = \phi_M A_M(\theta) + \phi_{Ba} A_{Ba}(\theta), \quad (4)$$

where the areas A_M and A_{Ba} are functions of the fractional coverage θ.

The term ϕ_{ML} A_{ML} is absorbed in the rate constants α and β that govern A_M and A_{Ba}. By taking this approach the areas A_M and A_{Ba} cannot be interpreted as geometric areas. They are weighted areas since they contain the monolayer work function.

The equation governing A_M and A_{Ba} are the rate equations

$$dA_M/d\theta = -\alpha A_M \quad (5)$$

and

$$dA_{Ba}/d\theta = -\beta A_{Ba} \quad (6)$$

The solutions to these two equations are simply

$$A_M = e^{-\alpha\theta} \quad (7)$$

and

$$A_{Ba} = 1 - e^{-\beta\theta} \quad (8)$$

with the appropriate boundary conditions ($A_M = 1$ when $\theta = 0$ and 0 when $\theta \rightarrow \infty$ and $A_{Ba} = 0$ when $\theta = 0$ and 1 when $\theta \rightarrow \infty$).

Writing out Equation 4, we get

$$\phi(\theta) = \phi_M e^{-\alpha\theta} + \phi_{Ba}(1 - e^{-\beta\theta}). \quad (9)$$

If we assume that at $\theta = \theta_m$ (where θ_m is the optimum coverage, not necessarily one monolayer), the net work function has a minimum, we can then place conditions on the rates α and β.

Differentiating Equation 9 and setting the result to zero, [i.e., $\phi'(\theta_m) = 0$] we get

$$(\Gamma\phi_M/\phi_{Ba})^{1/(1-\Gamma)} = e^{-\beta\theta_m} \quad (10)$$

where $\Gamma = \alpha/\beta$, the ratio of the relative covering rates.

We can then write an equation for the minimum work function $\phi(\theta_m) = \phi_m$,

$$\phi_m = \phi_M(\Gamma\phi_M/\phi_{Ba})^{\Gamma/(1-\Gamma)} + \phi_{Ba}\left[1 - (\Gamma\phi_M/\phi_{Ba})^{1/(1-\Gamma)}\right]. \quad (11)$$

The minimum work function is determined by one parameter, Γ, since ϕ_M and ϕ_{Ba} are known ($\phi_M = 4.5$ eV, for tungsten and $\phi_{Ba} = 2.55$ eV for Barium).

If we know ϕ_m, then we can determine Γ.

Once we know Γ, we have completely determined $\phi(\theta)$. If we take $\Theta = \theta/\theta_m$, we can write

$$\phi(\Theta) = \phi_M(\Gamma\phi_M/\phi_{Ba})^{\Gamma\Theta/(1-\Gamma)} + \phi_B\left[1-(\Gamma\phi_M/\phi_{Ba})^{\Theta/(1-\Gamma)}\right] \quad (12)$$

Figure 2 shows $\phi(\Theta)$ versus Θ, (Equation 12) as it compares to typical Ba on W data.(2)

RATE EQUATION FOR $\Theta(t)$

The model is now reduced to finding the time dependence of Θ. The total rate of change of the surface coverage can be thought of as increasing due to the evolution of active material from the matrix and decreasing due to surface evaporation; so we write

$$\frac{d\Theta}{dt} = \frac{E_o e^{-\epsilon/T}}{\sqrt{1 + \gamma t}} (1 - \Theta) - \frac{\Theta}{\tau}. \quad (13)$$

The coefficient $(1 - \Theta)$ is introduced, following Langmuir, to limit Θ to be less than 1. In effect, this means that as you approach $\Theta = 1$, the evaporation rate becomes so high that multiple layers cannot be sustained. The $(1 + \gamma t)^{-1/2}$ dependence come from considerations of Knudsen flow and accounts for both series and parallel conduction through the pores of the matrix.(3)

If we hold τ constant, the steady state solution of this equation becomes

$$\Theta(t) = \frac{E\tau}{E\tau + \sqrt{1 + \gamma t}} \quad (14)$$

where

$$E = E_o e^{-\epsilon/T}. \quad (15)$$

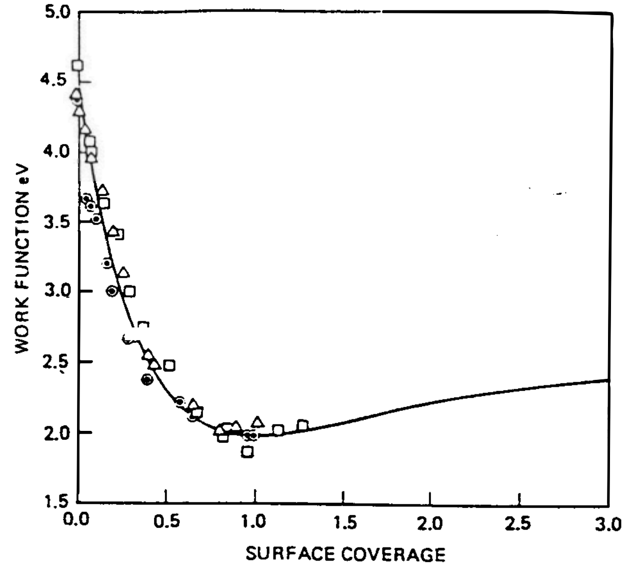

Figure 2 Comparison of work function vs surface coverage model with experimental data.

FITTING THE MODEL TO B-TYPE LIFE TEST DATA

We now have all the elements of the model except the coating. The Hughes accelerated life test data for B-type dispenser cathodes is used to calibrate the model.

Figure 3 shows the summary of the B-type cathode life test. The solid lines are the best fit using the model. The result for $\Theta(t)$ is

$$\Theta(t) = 3.12 \times 10^{-8} \exp\left[\frac{25900}{T}\right] \Big/ \left[3.12 \times 10^{-8} \exp\left(\frac{25900}{T}\right) + \sqrt{1 + .166t}\right], \quad (16)$$

where T is in Kelvin and t is in kilohours. As can be seen from Figure 3 the model quantitatively describes the experimental data.

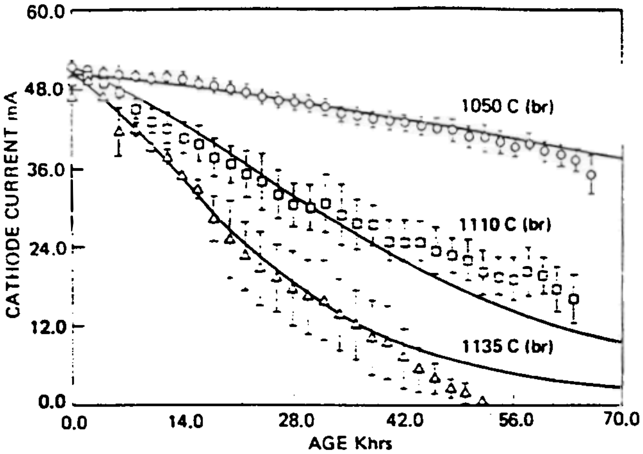

Figure 3 B-type accelerated Life Test run in a Pierce gun type device; Δ1135°C_{Br}, □1110°C_{Br}, O1050°C_{Br}.

M-TYPE CATHODE (COATING EFFECTS)

In order to complete the model we must include the effects of adding a coating on the surface. When dealing with a coated cathode, there is a second time dependent effect that must be considered. This is due to the interdiffusion of the substrate (tungsten) into the coating (osmium-ruthemium).

Let us take the coating to be of thickness d. The concentration of tungsten throughout the entire sample is determined by the diffusion equation

$$D \frac{\partial^2 C}{\partial x^2} = \frac{\partial C}{\partial t}, \qquad (17)$$

where D is the diffusion coefficient and C is the concentration of tungsten at a point x from the emitter surface and at time t.

Since we are only interested in the concentration of tungsten at the emitter surface, the solution reduces to

$$C(0,t) = (C_o - 1)\,\mathrm{erf}\left(\frac{d}{\sqrt{4Dt}}\right) + 1 . \qquad (18)$$

where C_o is the surface concentration of tungsten at t = 0, d is the coating thickness in micrometers and t is in kilohours.

In work described elsewhere,[4] a number of M-coated cathodes were studied using Auger Depth profiling after they had run various ages on life tests. That data provides us with an interdiffusion coefficient for tungsten and osmium-ruthenium given by

$$D(T) = 40.2\, e^{-12400/T}\ \mu^2/\mathrm{KHrs} . \qquad (19)$$

The boundary condition at t = 0 gives a surface concentration of tungsten of 30 percent. This is probably due to the annealing step in the manufacture of the cathodes.

The surface concentration of tungsten is then given by

$$C(0,t) = 1 - 0.7\,\mathrm{erf}\left(\frac{d}{\sqrt{4D(T)t}}\right) \qquad (20)$$

There are several ways we can incorporate this into the model:

1. We could incorporate the effect into τ, the sticking time, and assume that the workfunction versus coverage $\varphi(\Theta)$ is independent of the changes in the base metal alloy.
2. We can assume that the work function $\varphi(\Theta)$ changes with a change in the base metal. For example, $\varphi_M = 4.5$ for tungsten changes to $\varphi_M = 4.7$ for osmium with time.
   The minimum work function can also vary, or there can be a combination of these.

For this model, the second approach is taken. The parameter of the work function $\varphi(\Theta)$ varies with tungsten surface concentration by the relationship:

$$\varphi_M = 4.7 - 0.2\, C(0,t) \qquad (21)$$

for the base metal work function and

$$\varphi_m = 1.6 + 0.4\, C(0,t) \qquad (22)$$

for the minimum work function. In both case the surface tungsten concentration is given by Equation 20.

A COMPARISON OF THE MODEL WITH M-CATHODE ACCELERATED LIFE TESTS

The entire model is compiled and tested with experiments. Figure 4 shows a comparison of the model with accelerated life test data run in a TWT type electron gun.

The results of the model appear to be realistic.

We believe that the model meets our main objectives. It predicts the correct rate of current degradation as a function of temperature.

Figure 5 shows the M-type cathode life prediction calculation near the expected operating temperature of space TWT's. The model predicts long lives, of near 200,000 hours, with reasonably small current degradation. The M-type cathode is clearly superior to the uncoated cathode. Its advantage is almost entirely due to its lower operation temperature.

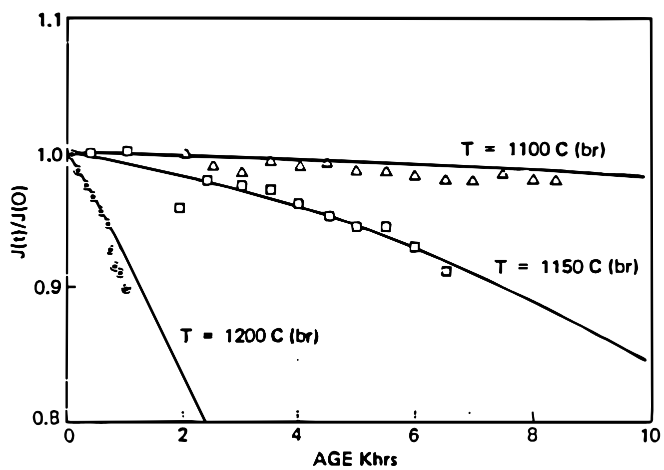

Figure 4 Accelerated M-type cathode run in a Pierce gun, initially set to be space charge limited.

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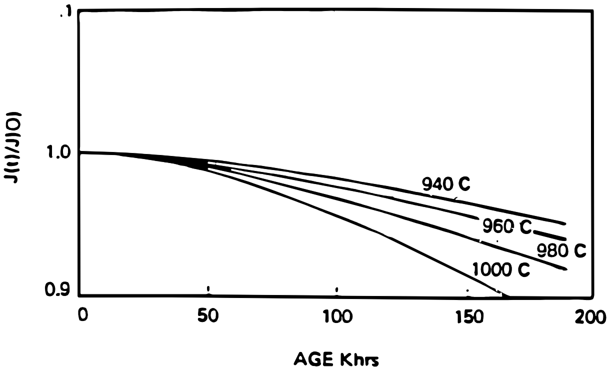

Figure 5 Model prediction near expected operating temperature for the M-type cathode. The coating thickness is initially 1 micrometer.

MAXIMUM CURRENT DENSITY FROM THE DISPENSER CATHODE

Although the model was generated to provide a means of calculating cathode life it contains within it another interesting prediction which is worthy of notice. The model suggests that if the temperature of the cathode is increased beyond 1400 to 1450°K the evaporation term will begin to dominate over the Ba supply term and Θ will decrease. Since ϕ is accelerating upward with a linear decrease in Θ, the increase in ϕ will dominate the temperature increase of the Richardson equation (Equation 1) and the total saturated current will begin to fall. Figure 6 shows the calculated saturated cathode current as a function of temperature.

The model predicts a maximum current from this dispensing type, surface monolayer cathode.

CONCLUSION

The life prediction model we have constructed provides a reasonably good description of the dispenser cathode current with time and temperature.

From an engineering point of view there are several point to be made: 1) the model provides us with an algorithm, with some rational behind it, to evaluate our products and to make some predictions; 2) the model and test data suggests that accelerated life tests are a valid way to evaluate our products; 3) the model predicts superior performance from the osmium-ruthenium coated cathode than from the uncoated cathode; 4) the prediction

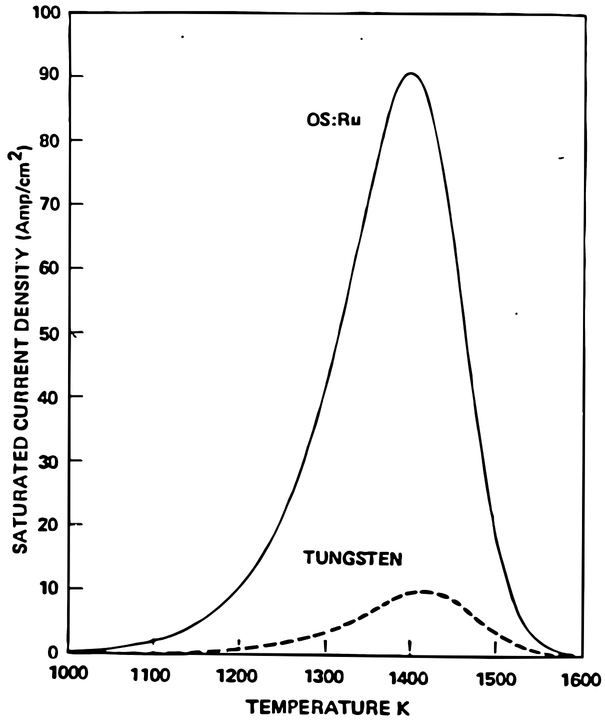

Figure 6 The model predicts a maximum saturated current density from each type of dispenser cathode.

of a maximum current from the dispenser cathode was somewhat unexpected and is currently under further investigation.

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