Section 7: Electrothermal Propulsion

AE435

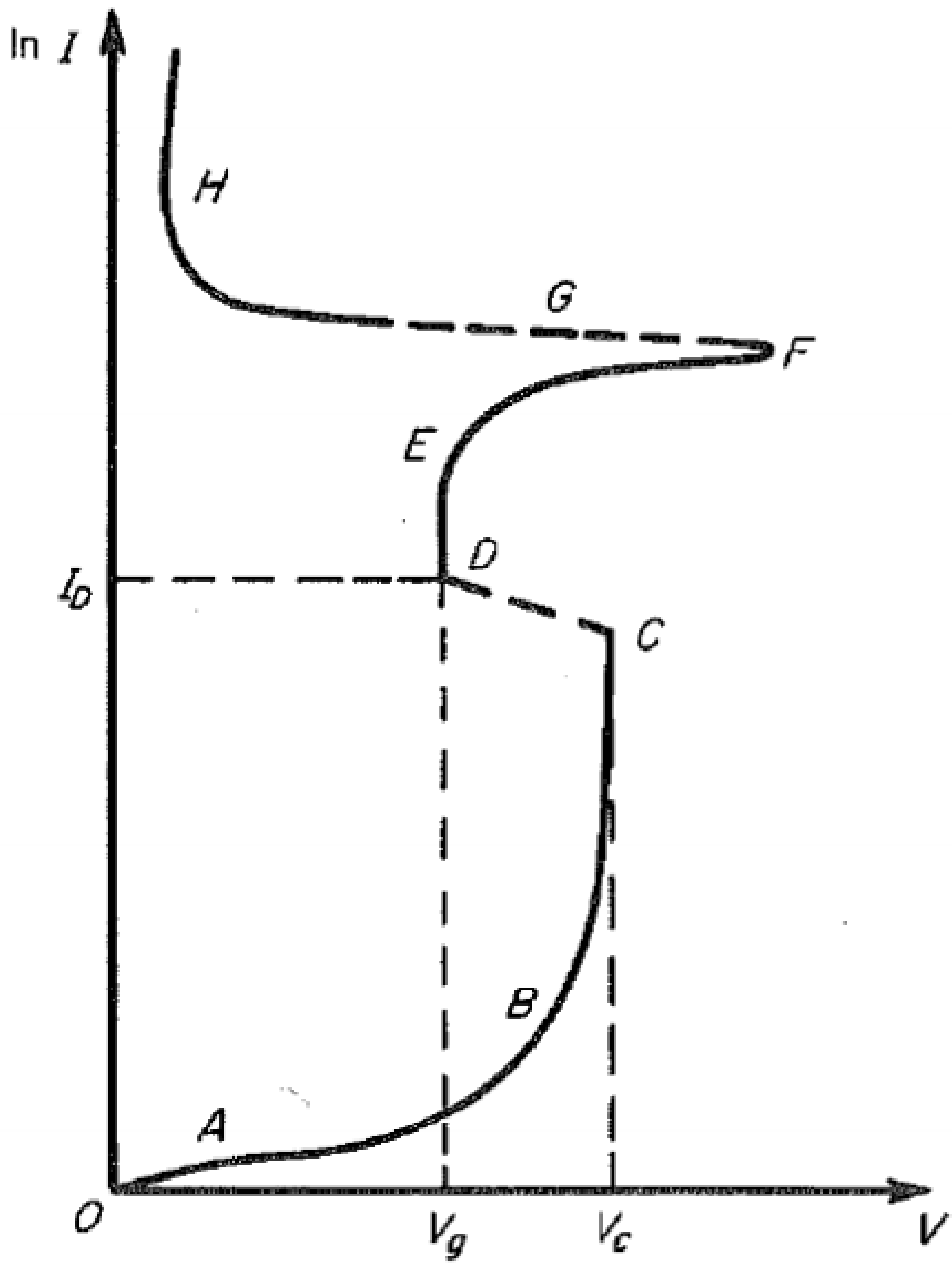
Spring 2018

2 Arcjets

Contents

2.1 Discharge Physics

Figure 6-12 in Jahn shows the electrical characteristic for a gaseous discharge. Starting at the lowest discharge current and heading upwards:



1. **O-A:** the stray charge region, here, ionization of gas is by background radiation, electrodes simply pick up bits of stray charge

2. **A-B:** the first Townsend region, where stray electrons pick up enough kinetic energy between collisions to ionize gas. The current, $J \propto$ External Radiation Source Intensity, and so this is where Geiger-Muller counters operate.

3. **B-C:** the 2nd Townsend region, where ions pick up enough kinetic energy from the E-field to cause **secondary electron emission** from the cathode.

Figure 12:

4. **C-D:** sparking and discharge, the curve here depends on
    - Power supply characteristics
    - Gas pressure
    - Electrode material
    - Electrode shape
        - In particular,
            - Sharp points and/or high pressure lead to a **corona discharge**.

Figure 13:

- Blunt electrons and/or low pressure lead to a **glow discharge**.

Figure 14:

- Electrode spacing

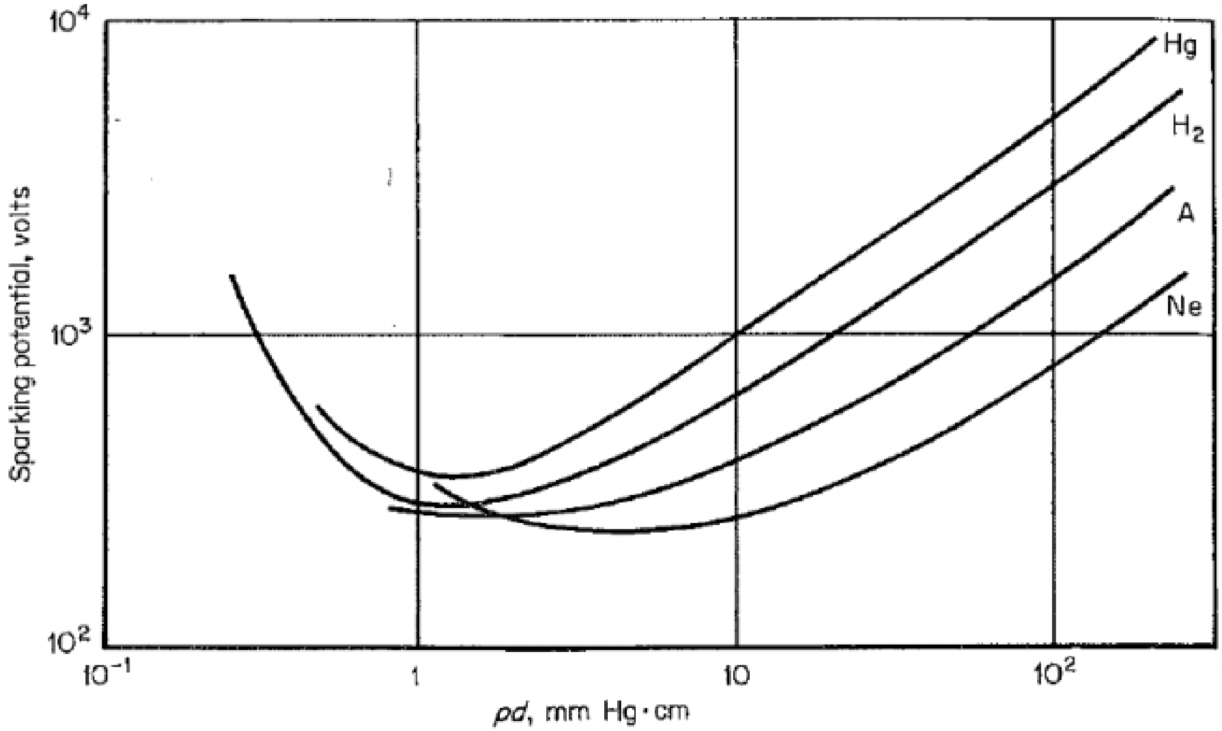


Fig. 6-13 Sparking potential for various gases (Paschen's law). (*From A. von Engel, "Ionized Gases," chap. 7, p. 172, Oxford University Press, Fair Lawn, N.J.,* 1955.)

Figure 6-13 in Jahn shows "Paschen curve" of Vc as a function of p d, where

- p is the pressure
- d is the electrode gap

5. **D-E:** normal glow discharge, characterized by:
   - Constant current density (10-3 to 1 A/cm2)
   - High Te and low Ti TA
   - Voltage drop primarily in cathode sheath
6. **E-F:** abnormal glow discharge, where
   - Cathode drop starts to increase with current
   - Cathode heating grows proportionally

7. **F-G:** glow-to-arc transition, where the cathode temperature Tc increase until thermionic emission starts to predominate. The governing equation is:

Richardson-Duschman Relation

$$j_e = A_r\, T_c^2\, \exp\left[\frac{-\Phi_{eff}}{k\, T_c}\right] \tag{7.72}$$

Where

$$A_r = 60 \quad \left[\frac{A}{cm^2\, K^2}\right] \tag{7.73}$$

and...

Effective Work Function

$$\Phi_{eff} = \Phi_w - \sqrt{\frac{q_e\, E_c}{4\,\pi\,\varepsilon_o}} \tag{7.74}$$

Where

Φ_w = Zero-Field Work Function

E_c = Electric-Field Magnitude at the Cathode Surface

Lowering the work function increase the emission current density.

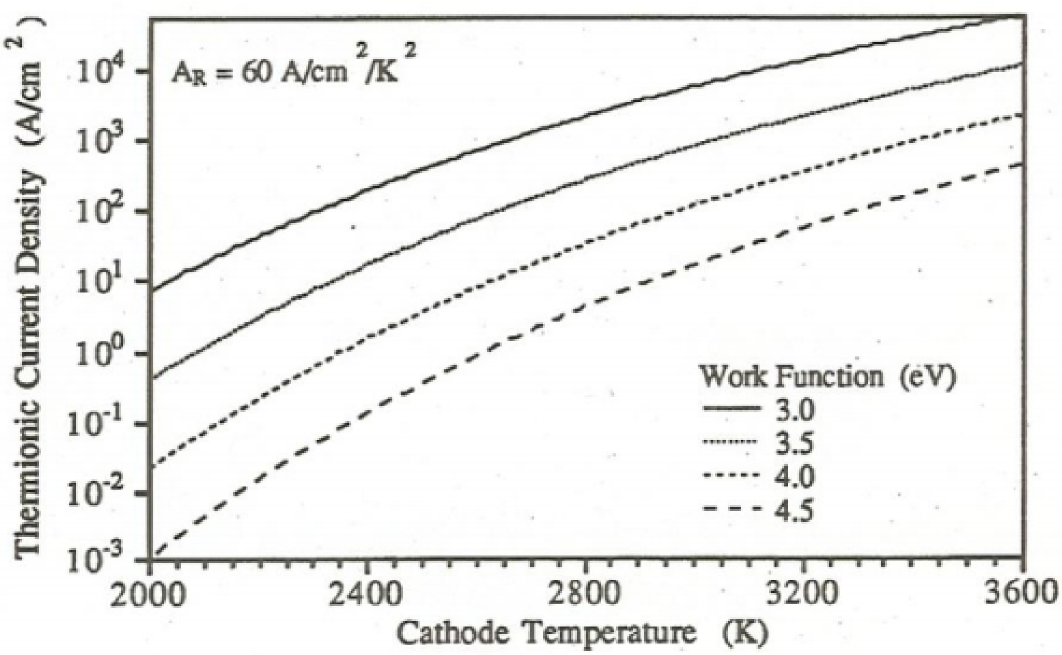


Figure 2.2: Effect of material work function on thermionic emission current.

Typical work functions for metal surfaces:

Metal	Φ_w (V)
Si	4.90
Ni	4.50
Mo	4.30
W	4.54

Increased electric field has the same effect as lower work function:

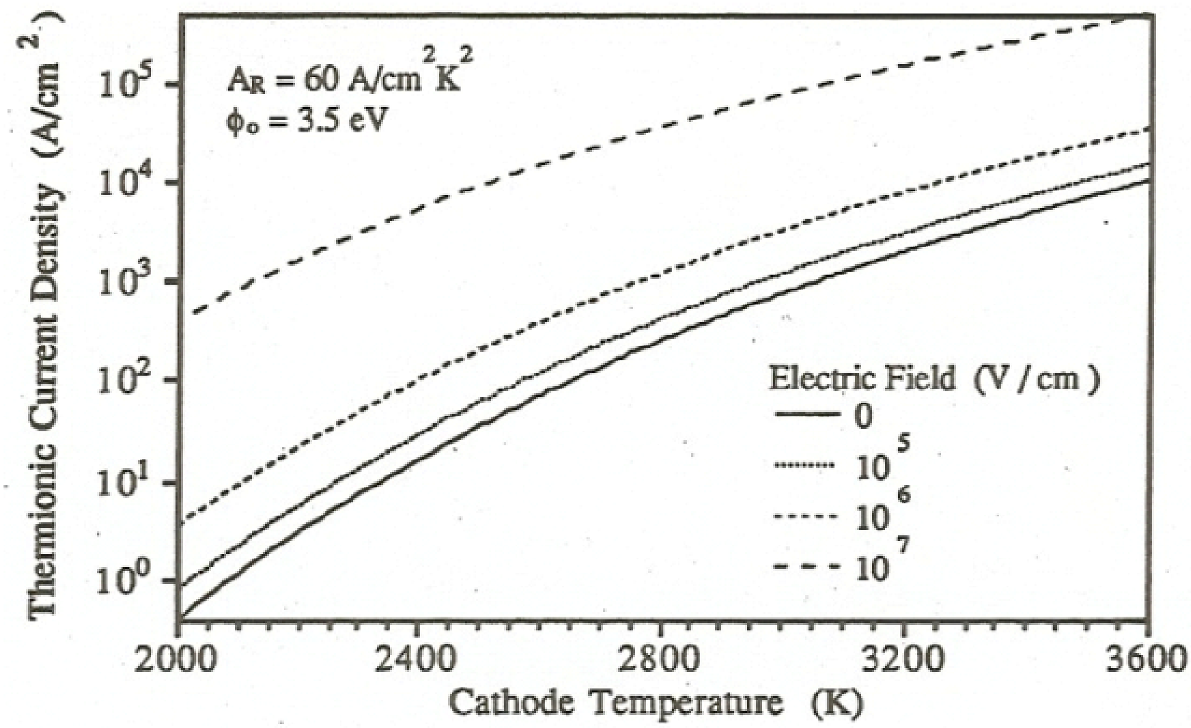
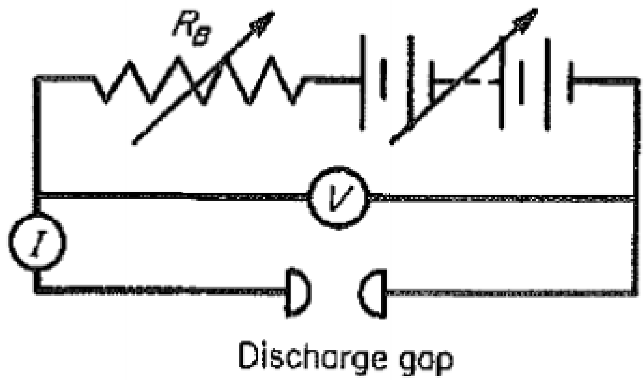


Figure 2.3: Effect of surface electric field on thermionic emission current.

Once thermionic emission sets in, the cathode drop decreases and the current increases. The cathode temperature (and, thus, the emission current density) is regulated by the energy balance:

- Heating: Ion bombardment and radiation
- Cooling: Conduction (to gas and solids), radiation, convection and electron emission

8. **G-H:** Arc, with resistance dropping rapidly enough that prompt kA currents, can vaporize electrodes. Classic fix, place a ballast resistor in series with the circuit:



$$V_B = I\,R_B$$
$$V_{tot} = V_B + V_{gap} \tag{7.75}$$

As the current increases, the voltage drop across RB increases, preprventing "runaway".

Note that G-H is the regime of interest for ET arcjet propulsion.

2.2 Arc Physics

2.3 Modeling Approaches