Thermionic Energy Conversion

Definition

" A thermionic converter is a static device that converts heat into electricity by boiling electrons from a hot emitter surface (≈1800 °K) across a small inter electrode gap (< 0.5 mm) to a cooler collector surface (≈ 1000 °K)"

Note: Since this is a form of a heat engine, it is limited by the Carnot efficiency, at best.

History

Edison-1883.....discovered release of electrons from a hot body

Fleming-1904.....Invented themionic diode rectifier

Schlicter-1915.....First proposed thermionic conversion

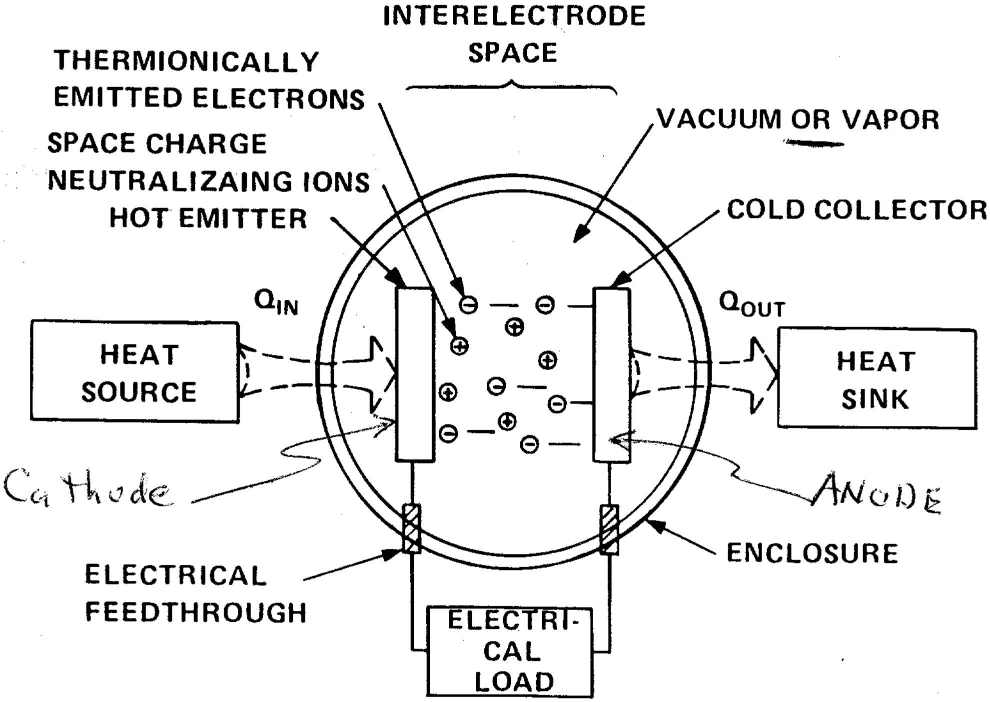
Serious work on thermionic devices began in the early 1950's

Components of Thermionic Converter- Figure

- **Anode must be kept cool to avoid back emission of electrons**
- **Note Potential for Topping cycle**
- **If the gap contains only a vacuum it is called a vacuum diode,..if it contains a vapor, it is called a plasma diode.**

Factors that limit the efficiency of energy transfer in a thermionic device

THERMIONIC CONVERTERS



TYPICAL OPERATING REGIME

EMITTER TEMPERATURE: 1600–2000 K (2420–3140°F)
COLLECTOR TEMPERATURE: 800–1100 K (980–1520°F)
ELECTRODE EFFICIENCY: UP TO 20%
POWER DENSITY: 1–10 W/cm^2

MATERIALS

EMITTER MATERIALS: W, Re, Mo
COLLECTOR MATERIALS: Nb, Mo
INSULATOR MATERIALS: Al_2O_3, Al_2O_3/Nb CERMET
ELECTRODE ATMOSPHERE: Cs AT 1 Torr

Fig. 5.31 Schematic of thermionic converter [12].

1.) **Radiation heat transfer between the cathode and the diode,**

2.) **Space charge effect that limits the flow of electrons,**

3.) **Thermal energy losses to the environment.**

Principles of Operation

Electron distribution follows Fermi-Dirac Law;

$$n(E)dE = \left[\frac{4\pi(2\mathrm{m}_{\mathrm{e}})^{\frac{3}{2}}}{h^3}\right]\left\{\frac{\sqrt{E}}{1+\exp\left(\frac{E-E_F}{kT}\right)}\right\}dE$$

Probability that any energy state is occupied:

$$P(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)}$$

Where $E_F = \left[\frac{h^2}{2m_e}\right]\bullet\left(\frac{3n}{8\pi}\right)^{\frac{2}{3}}$

n= # of free electrons/unit volume

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Figures (2) + Graph

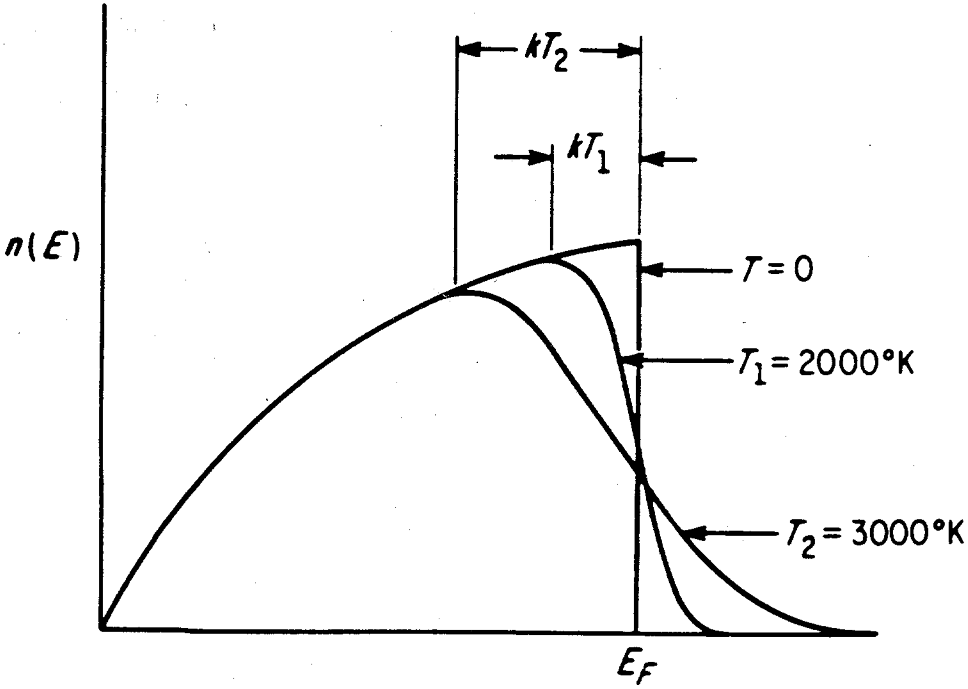


FIG. 13-2. Energy distribution of an electron gas at different temperatures.

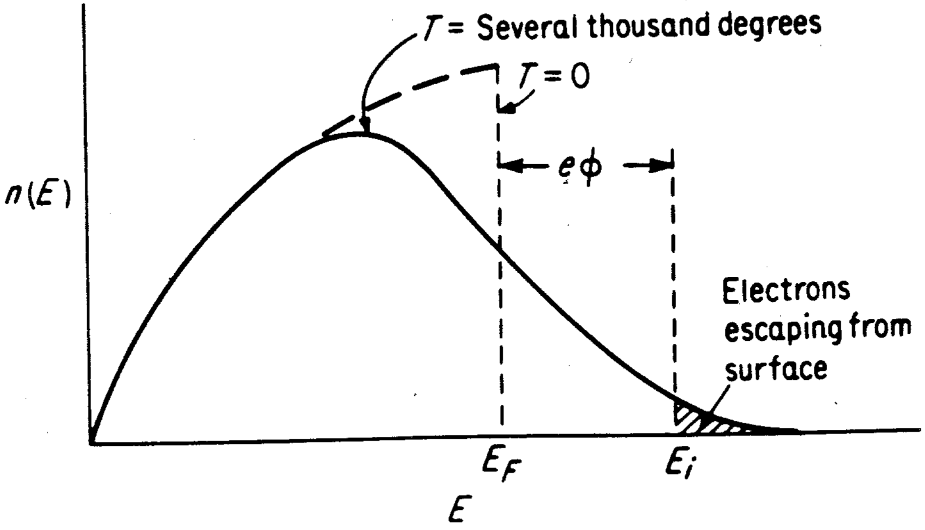


FIG. 13-6. Electron energy distribution at high temperatures showing electrons with sufficient energies to escape from surface.

In order for an electron to escape the surface it must have sufficient energy to move it from the Fermi surface to a point outside the metal.

That energy, per unit charge, is called the work function,Φ. We designate the work function of the emitter (cathode) as Φ_E and that for the collector (anode) as Φ_c.

Note $V = \Phi_E - \Phi_c$

For the time being , assume that no space charge or other phenomena limit the current flow. For an ideal diode one gets the Richardson-Dushman equation.

$$J\left(\frac{amps}{cm^2}\right) = AT_E^2 \exp\left(-\frac{\Phi_E}{kT_E}\right)$$

where

- **A depends on material and ranges from**

$$3\text{-}100\ \frac{amps}{cm^2 \circ K^2}$$

Note; as long as $V+\Phi_c<\Phi_E$, the barrier to electron flow is Φ_E and the current is independent of the thermionic device voltage and is called the saturation current.

$$J\left(\frac{\mathrm{amps}}{\mathrm{cm}^2}\right) = AT_E^2 \exp\left(-\frac{11{,}600\Phi_E}{T_E}\right)$$

where T =°K, Φ_E=volts

However, when the $\Phi_c+V>\Phi_E$, then the barrier is Φ_c+V, and any increase in V will reduce J.

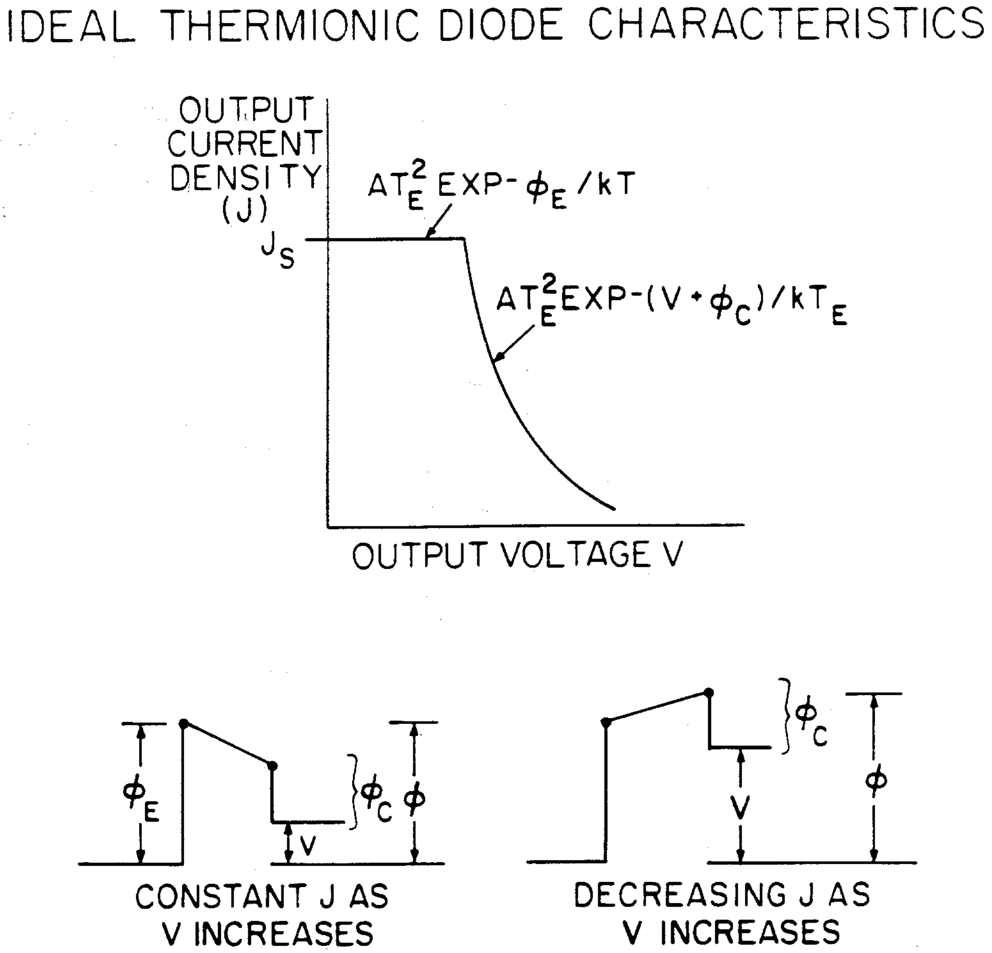


Fig. 5.32 Ideal thermionic diode characteristics [*1*].

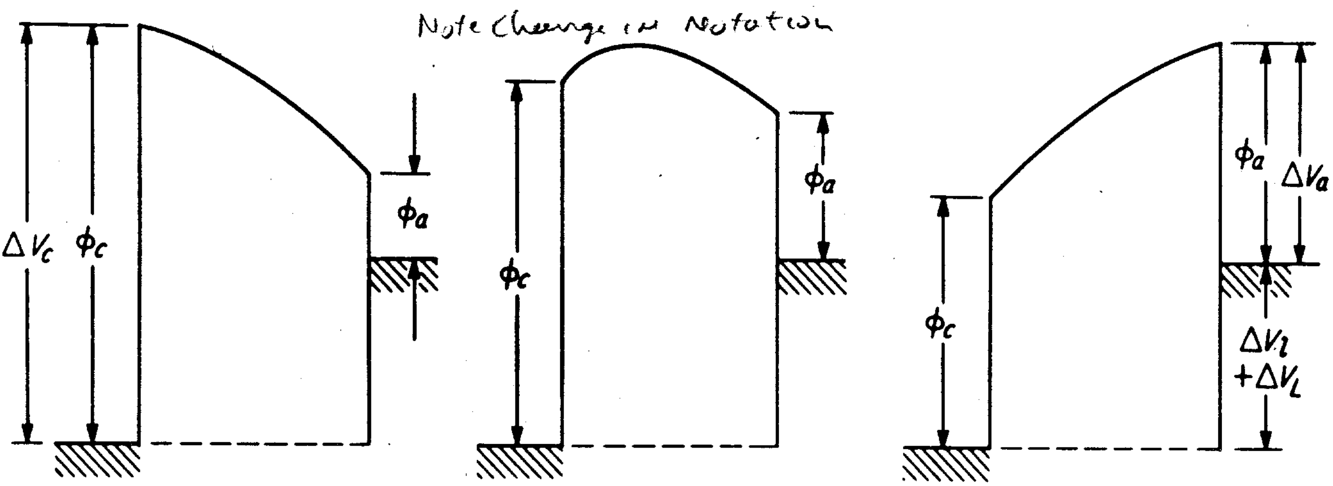
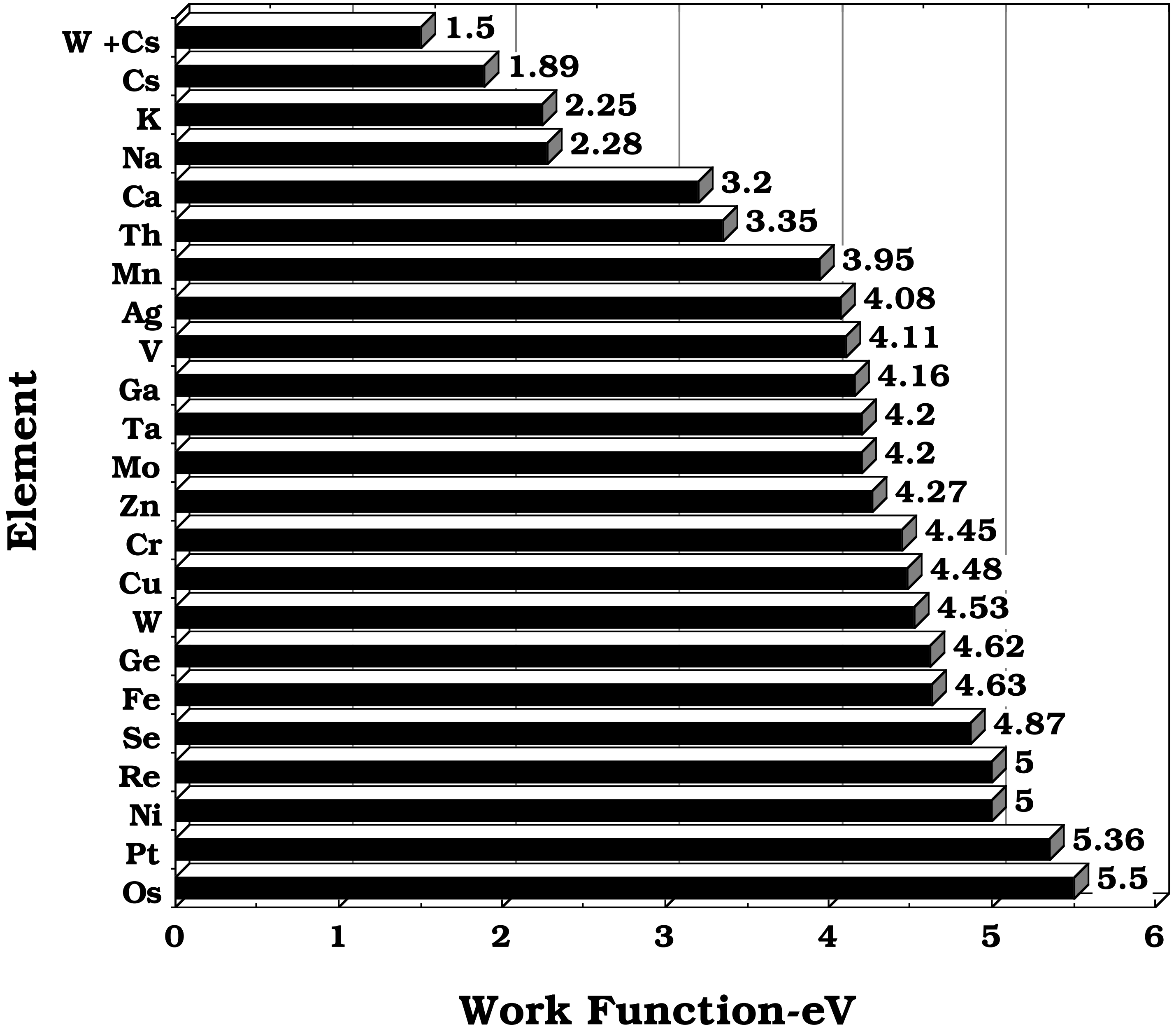
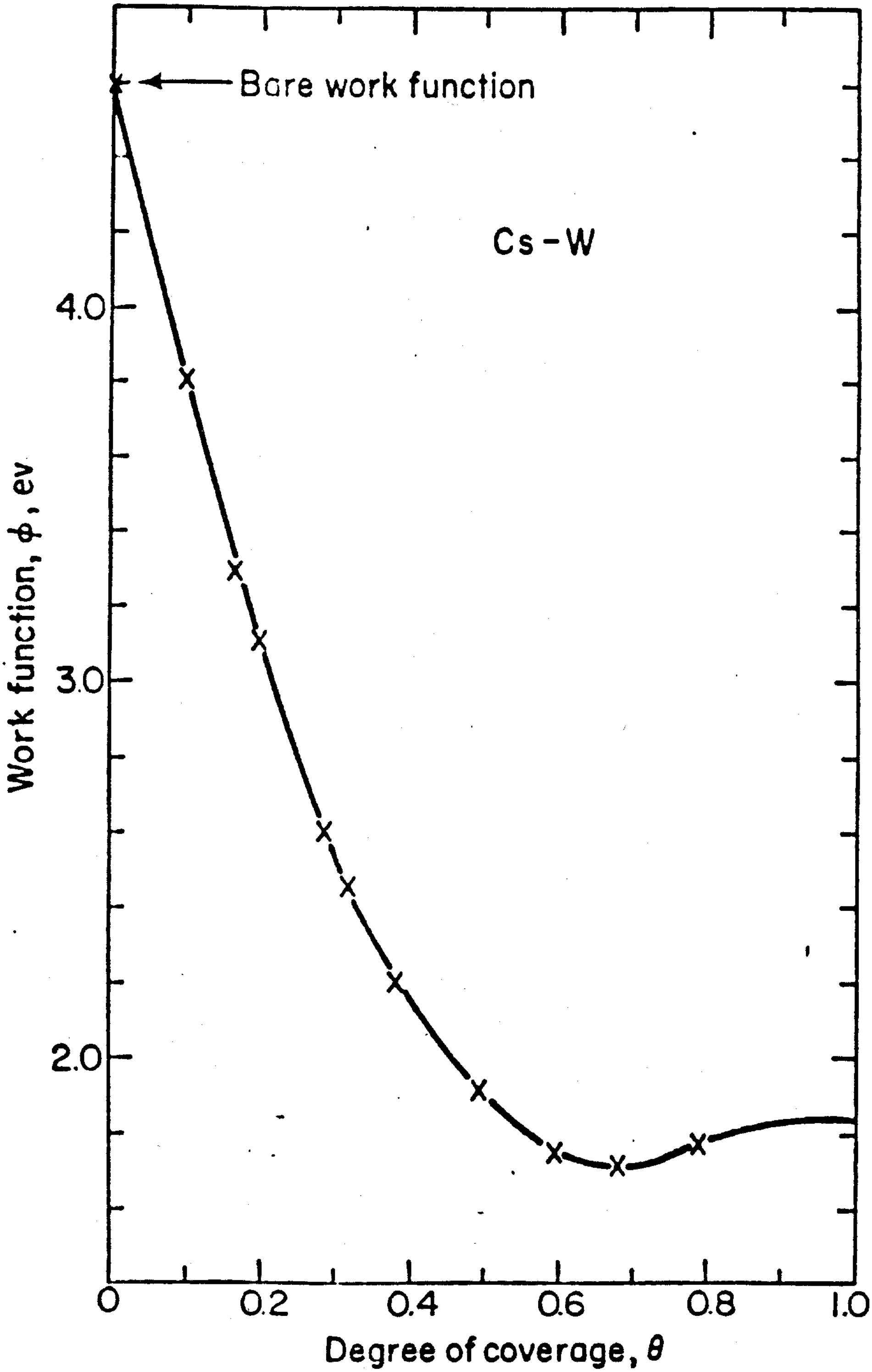

Note Change in Notation

FIG. 13-8. Three interelectrode potential profiles for the same ΔV_c, ΔV_a and $\Delta V_l + \Delta V_L$

Work Function Values for Metallic Elements



Work function, ϕ, vs. degree of coverage, θ, for a cesiated-tungsten surface.



Problem is that work functions are too high (to get 1 amp/cm^2 from W need to run at 2600 °K)

Solution: Use Cs to Lower work function.
(See 2 Graphs)

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Space Charge Effects

Once the electron cloud builds up between the electrodes, the flow of electrons from the emitter is retarded by an additional potential, ΔV_{EB} (Barrier Index). Adding in the voltage loss across the leads ΔV_{ℓ} and the voltage loss across the load, ΔV_L,

See Figure

$$J = AT_E^2 \exp\left(-\frac{(\Phi_E + \Delta V_{EB})}{kT_E}\right)$$

or

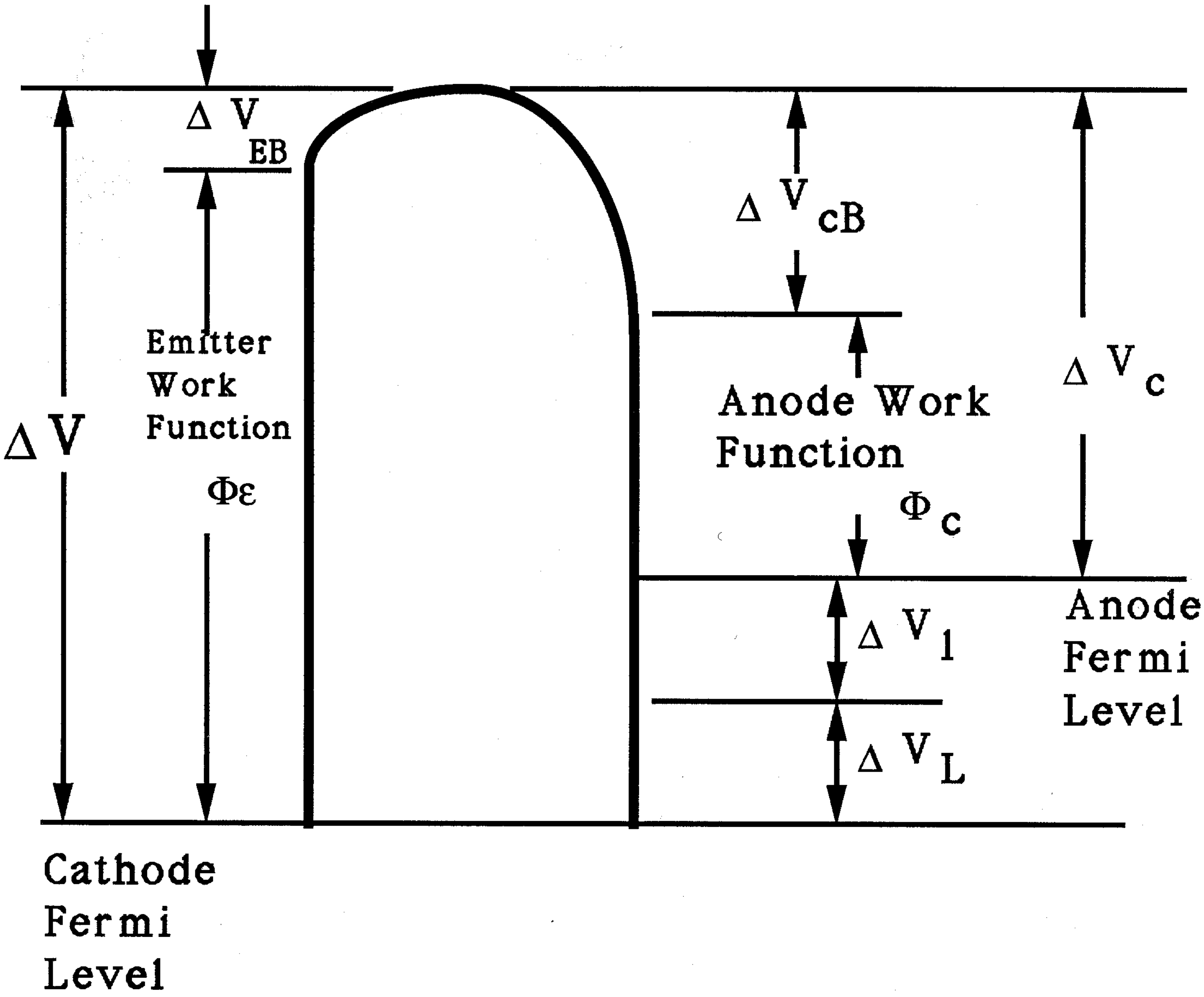
$$J = AT_E^2 \exp\left(-\frac{(\Phi_c + \Delta V_{cB} + \Delta V_{\ell} + \Delta V_L)}{kT_E}\right)$$

Major difficulty with Thermionics;

- ***Large current requires small work function,***
- ***Large voltage ($V=\Phi_E-\Phi_C$) requires large work function.***

Efficiency of Vacuum Diodes

Potential Diagram of a Thermionic Vacuum Diode



Determined by power losses

a.) Radiation Heat Losses

b.) Heat Conduction and I^2R Losses.

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Radiation Heat Losses

$$P_r = \left(\frac{\sigma\left[T_E^4 - T_c^4\right]}{\left\{\left(\frac{1}{\varepsilon_E}\right) + \left(\frac{1}{\varepsilon_c}\right) - 1\right\}} \right)$$

Heat loss can be reduced by using materials with low emissivities

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Heat Conduction and I^2R Losses

Conduction

$$P_k = \left(\frac{k_\ell A_\ell}{A_E}\right) \bullet \left(\frac{T_E - T_L}{\aleph}\right)$$

= heat /unit area of emitter(conduction from anode neglected)

where A_E **= area of emitter (cathode)**
k_ℓ**= thermal conductivity of lead**
A_ℓ **= Cross-sectional area of lead**
$\aleph$ **= length of electrical lead**
T_L **= temperature of load**

I^2R

$$P_j = \left\{\frac{1}{A_E}\right\}(I_n A_E)^2 R_\ell$$
(heat load per unit area of emitter)

R_ℓ **= electrical resistance of lead**

- **Assume that 1/2 of loss flows toward cathode**

Combined losses from the cathode

$$P_{k,j} = \left\{\frac{1}{A_E}\right\}\Sigma\left\{\left[\frac{k_\ell A_\ell (T_E - T_L)}{\aleph}\right] - \left[\frac{(I_n A_E)^2 R_\ell}{2}\right]\right\}$$

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Efficiency of diode, η, is,

$$\eta = \frac{P_L}{P_e + P_r + P_{k,j}}$$

where $P_L = I_n \Delta V_L$ (useful heat load/unit area of emitter)

P_e **= Potential energy imparted to the electrons + K.E. at emitter temperature**

$$P_e = I_n\left(\Delta V_E + \frac{2kT_E}{e}\right)$$
$$= I_n\left(\Delta V_L + \Delta V_\ell + \Delta V_c + \left\{\frac{2kT_E}{e}\right\}\right)$$

(e is the charge on the electron)

and $\Delta V_\ell = I_n A_E R_\ell$

using; $\rho_{\ell} = \frac{R_{\ell} A_{\ell}}{\aleph}$

and Wideman-Franz law

$$\rho_{\ell} k_{\ell} = \left(\frac{\pi^{2}}{3}\right) \bullet \left(\frac{k}{e}\right)^{2} \bullet T_{\ell}$$

where $T_{\ell} = \frac{(T_{E} + T_{L})}{2}$

$$\eta = \frac{I_{n} \Delta V_{L}}{\left[I_{n}\left(\Delta V_{L} + I_{n} A_{E} R_{l} + \Delta V_{c} + \frac{2kT_{E}}{e} \right) + P_{r} + \frac{\pi^{2}\left(\frac{k}{e}\right)^{2}\left(T_{E}^{2} - T_{L}^{2}\right)}{6 A_{E} R_{l}} - \frac{I_{n}^{2} A_{E} R_{l}}{2} \right]}$$

Maximizing $\frac{d\left(\frac{1}{\eta}\right)}{dR_{\ell}} = 0$

See El Wakil, Nucl. Energy Conversion, Ch. 13

$$\eta_{\max} = \frac{1}{1 + \Gamma}$$

and current at $\eta_{\max}$**,** $I_{n}^{*} = \left(\frac{eP_{r}}{kT_{E}}\right) \bullet \left(\frac{1}{\Gamma}\right)$

and

$$\Gamma = \frac{\left(\frac{e\Delta V_c}{kT_E}\right) + 2 + \pi\sqrt{\frac{2(1+2\Gamma)}{3}}}{\ln\left(\frac{AkT_E^3}{eP_r}\right) + \ln\Gamma - \left(\frac{e\Delta V_c}{kT_E}\right) - 1}$$

Problem-Calculate the efficiency of the thermionic diode with the following characteristics;

I_n = 100 amp   Emitter area =10 cm^2

e_E = 0.25 T_E = 1800 °K

e_c =0.50 T_c = 800 °K

$$P_r = 5.67x10^{-12}\frac{\left[\left(1800^4 - 800^4\right)\right]}{\left(\frac{1}{0.25}\right)+\left(\frac{1}{0.5}\right)-1}$$

P_r = 11.34 Watts/cm^2

and I_n =100/10 = 10 amps/cm^2

$$\Gamma = \left(\frac{eP_r}{kT_E I_n^*}\right) = \left(\frac{11.34 \bullet 11{,}600}{10 \bullet 1800}\right) = 7.31$$

and efficiency = $\frac{1}{1+\Gamma} = \frac{1}{8.31} = 12.03\%$

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<u>Miscellaneous</u>

- **In vacuum diode, the gap is reduced to a few micons to reduce space charge. The gaps can be a problem for thermionic units near to nuclear fuel which can swell much more than that.**

- **One solution is to 'cesiate' the surfaces to lower the work function and neutralize the plasma in the gap (now the spacing can be as much as 50 microns).**

- **Present devices achieve less than half of Carnot (≈ 10 - 15 %) but other attractive features keep thermionics 'in the hunt'.**
  - **Absence of rotating machinery**
  - **Compactness**
  - *** Work well at high temperatures**
  - **Higher efficiency than thermoelectrics**

Arrangement for Power Sources

A.) In pile;

Figure 13-15

- **Cathode directly heated by fissioning fuel.**

Figure 13-18

- **Anode cooled by liquid metals**

B.) Surface Concept;

Thermionic cells placed in contact with the outside of the compact core

C.) Out-of - pile;

Cells placed in the exterior of the reactor.

Figure 13-16

Advantage is very little radiation damage to elements.

Figure

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In - Pile Convertors

Common fuel materials;
UC, UC-ZrC, UO_2 and UO_2 -W

Example UC, can be used as an unclad emitter.

Major problem is the swelling of the fuel and closing of the gap.

Solution; encase the fuel with a refractory metal,
Penalty; loss in work function

Tantalum used originally but ran into embrittlement, also not corrosion resistant........ moved to Re then later to Mo

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Isomite (Figure 13-21)

- **small power (few Watts)**
- **low efficiency (0.3 -3.4 %)**
- **Pacemakers**

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Figure-Comparisons of Operating Temperatures

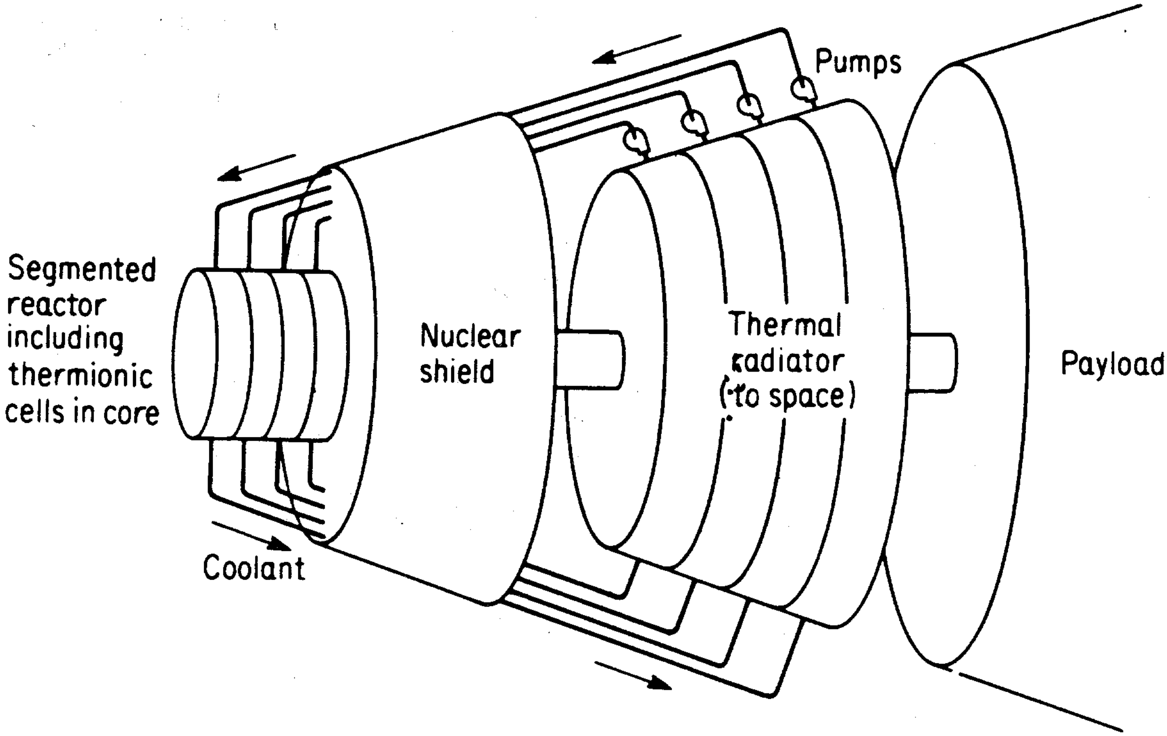


FIG. 13-15. Schematic drawing of an in-pile nuclear thermionic power system for space applications.

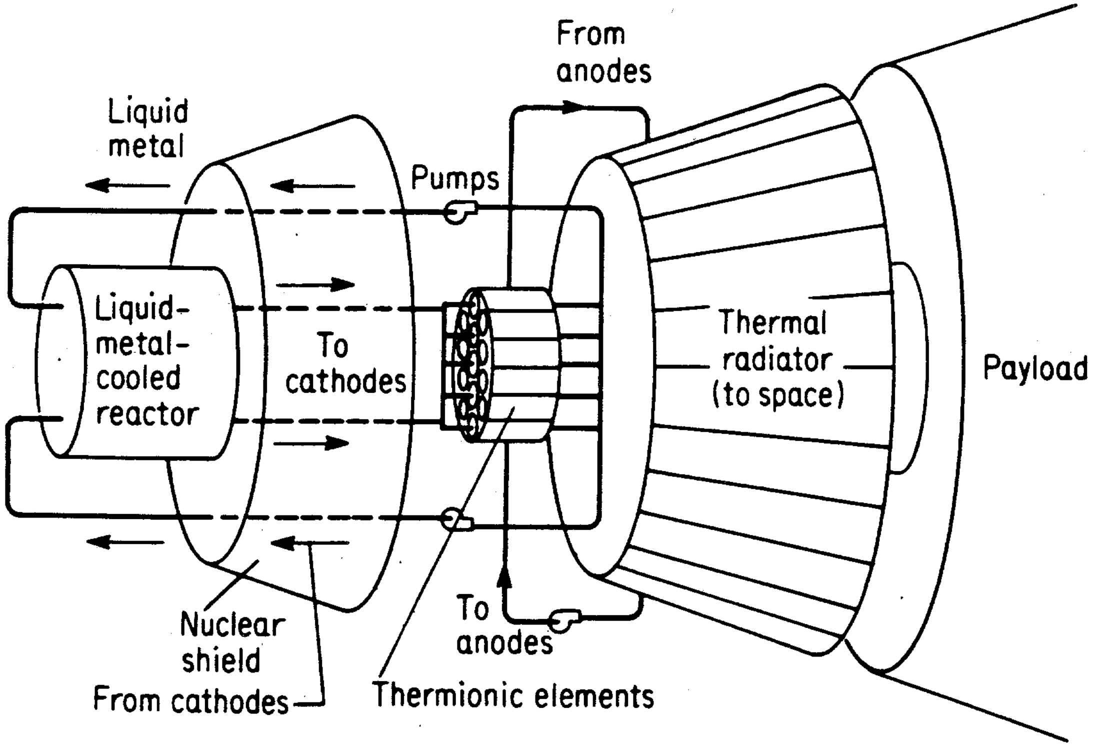


FIG. 13-16. Schematic drawing of an out-of-pile nuclear thermionic power system for space applications.

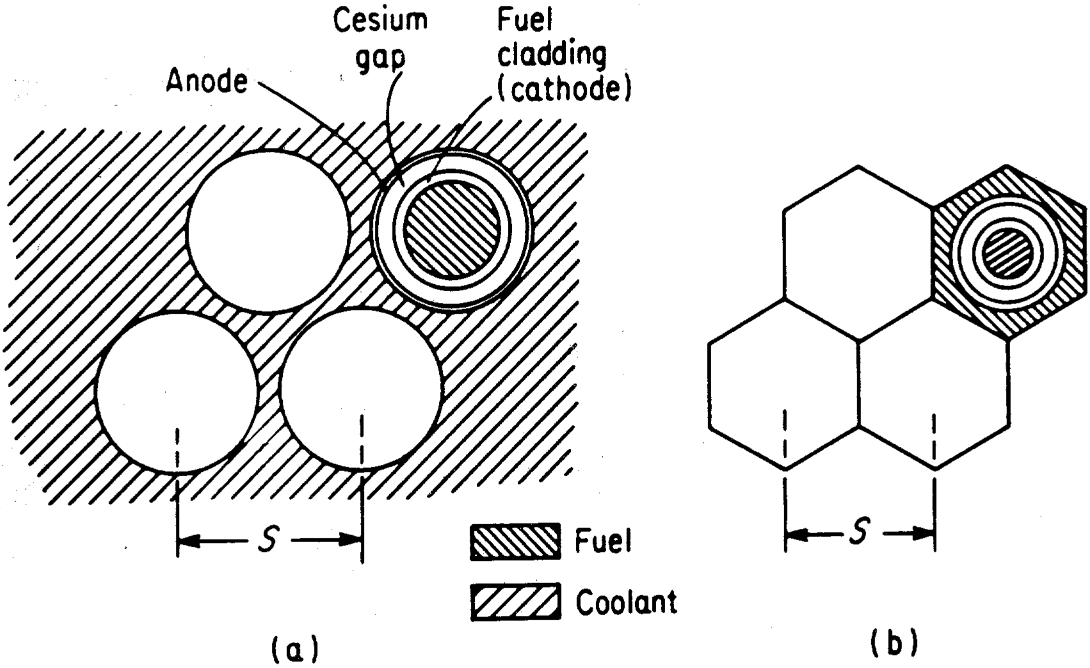


FIG. 13-18. In-pile thermionic cell arrangements: (a) internal fuel, (b) external fuel. (Ref. 137.)

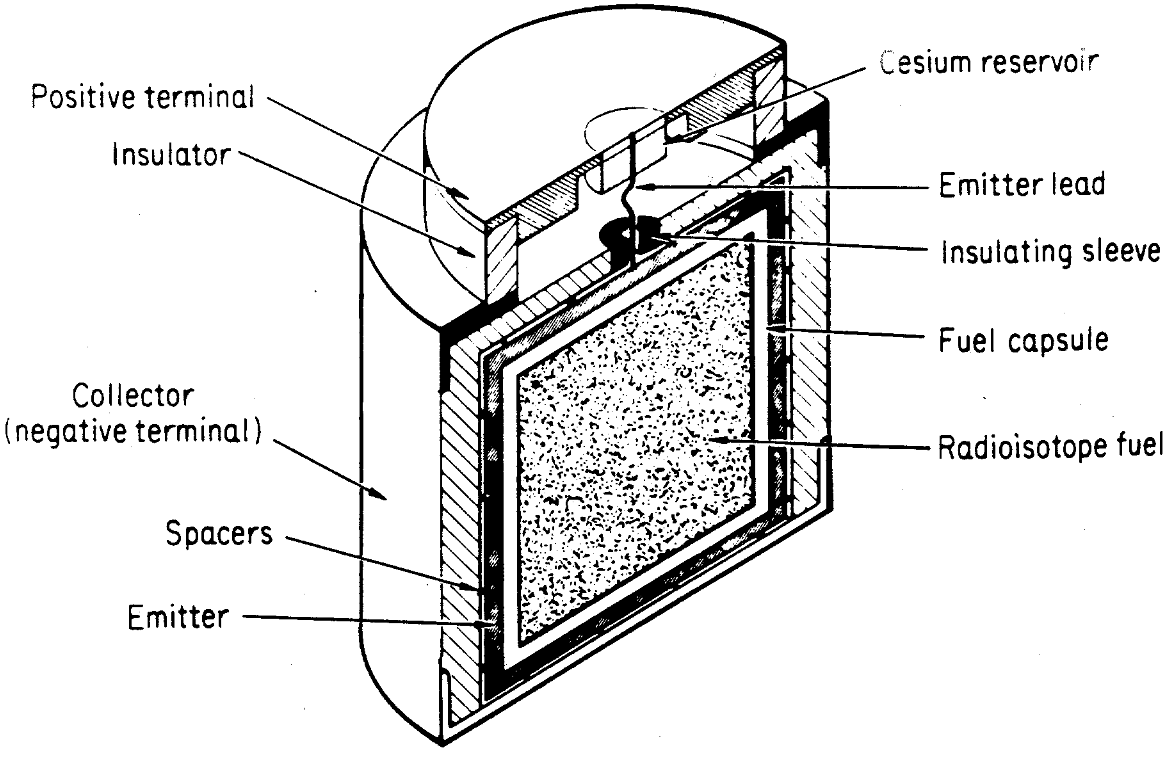
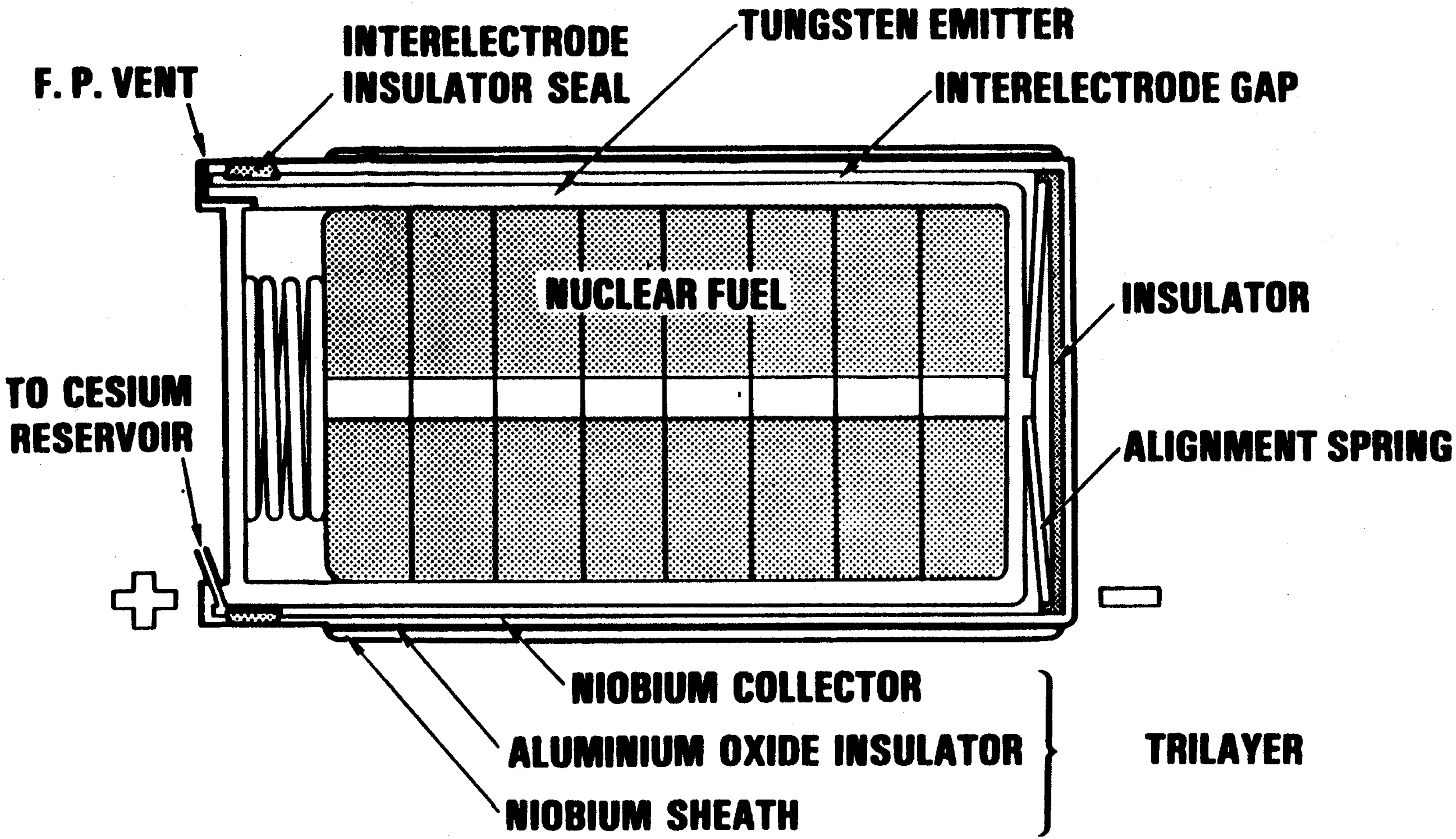
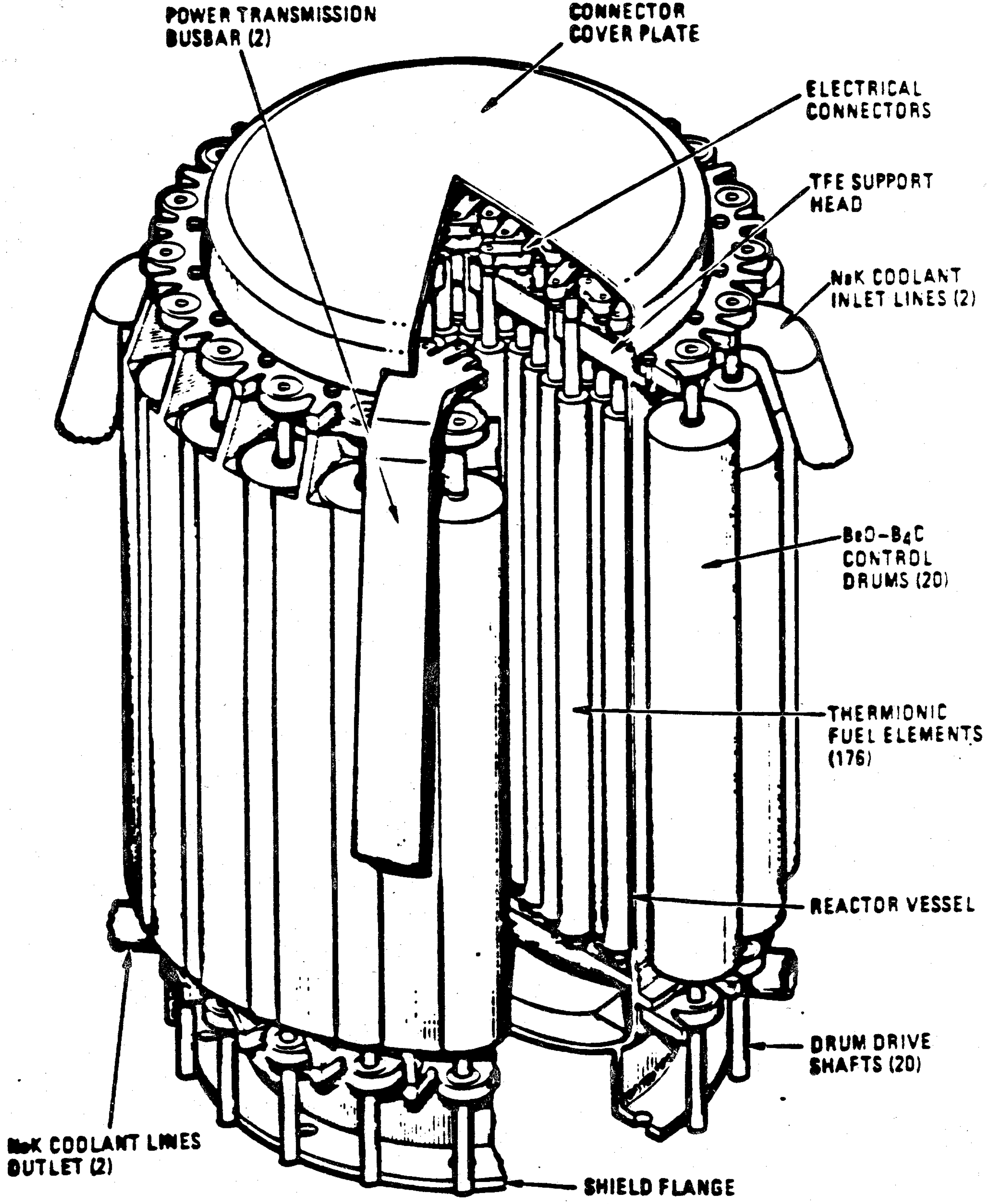


FIG. 13-21. Isomite thermionic power cell. (Courtesy McDonnel Douglas Astronautics Company.)

SCHEMATIC OF IN-CORE THERMIONIC CELL



FAST SPECTRUM THERMIONIC REACTOR



Comparison of Critical Material Temperatures for Static Conversion Systems