Chapter Two
Direct Energy Conversion

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Outline

- Introduction
- Topping and tailing
- MHD
- Thermoelectric
- Thermionic
- Fuel cell
- Photovoltaic

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Indirect energy conversion

- Generation of electricity involves various energy conversion processes.
- For example: a steam power plant operated on fossil fuel involves several energy conversion steps: The combustion of fuel converts the chemical energy to thermal energy; the expansion of steam in the turbine converts the thermal energy to mechanical energy, which can be converted later into electrical power using a generator.

Direct energy conversion

- Direct energy conversion means the generation of electrical power by converting directly from the available form of energy without passing through the various energy conversion forms.
- Thermal energy can be converted directly into electrical energy in the Magneto-hydrodynamic MHD generator, thermoelectric converter, or thermionic converter.

Direct conversion

- The electromagnetic energy can be converted directly into electricity in the photovoltaic or the solar cells.
- The chemical energy in some fuels may be converted to electrical energy using a Fuel Cell and the batteries.
- Mechanical energy can be converted into electricity in the conventional generator or alternator or in a fluid-dynamic converter such as an MHD system.

Advantages of direct energy conversion systems

- The elimination of the intermediate step of converting into mechanical energy and its moving parts.
- In some systems such as Fuel-Cell, the conversion efficiency is not limited by the second law of thermodynamics
- Disadvantages: additional cost.

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Topping device

- For most of the heat engines, there is a range between the available flame temperature and the upper temperature open to thermodynamic exploration.
- Topping is the concept of making use of this temperature range. Its practical exploitation depends on developing methods and materials to handle the high temperature.

Topping device

- It uses the upper temperature range (above the conventional system range). Conventional range up to around 1000K.
- It uses the temperature range of the combustion/ flame temperature and the upper limit of conventional system.
- It does not use any part of the temperature range of the conventional plants, hence it improves the overall cycle efficiency at the expense of some increase in the initial cost.

Combined cycle power plant

- The Combined Cycle Power Plant or ***combined cycle gas turbine***, a gas turbine generator generates electricity and waste heat is used to make steam to generate additional electricity via a steam turbine.
- A Combined Cycle Power Plant produces high power outputs at high efficiencies (up to 55%) and with low emissions. In a Conventional power plant we are getting ***33% electricity only*** and remaining 67% ***as waste***.
- By using combined cycle power plant we are getting ***68% electricity***.

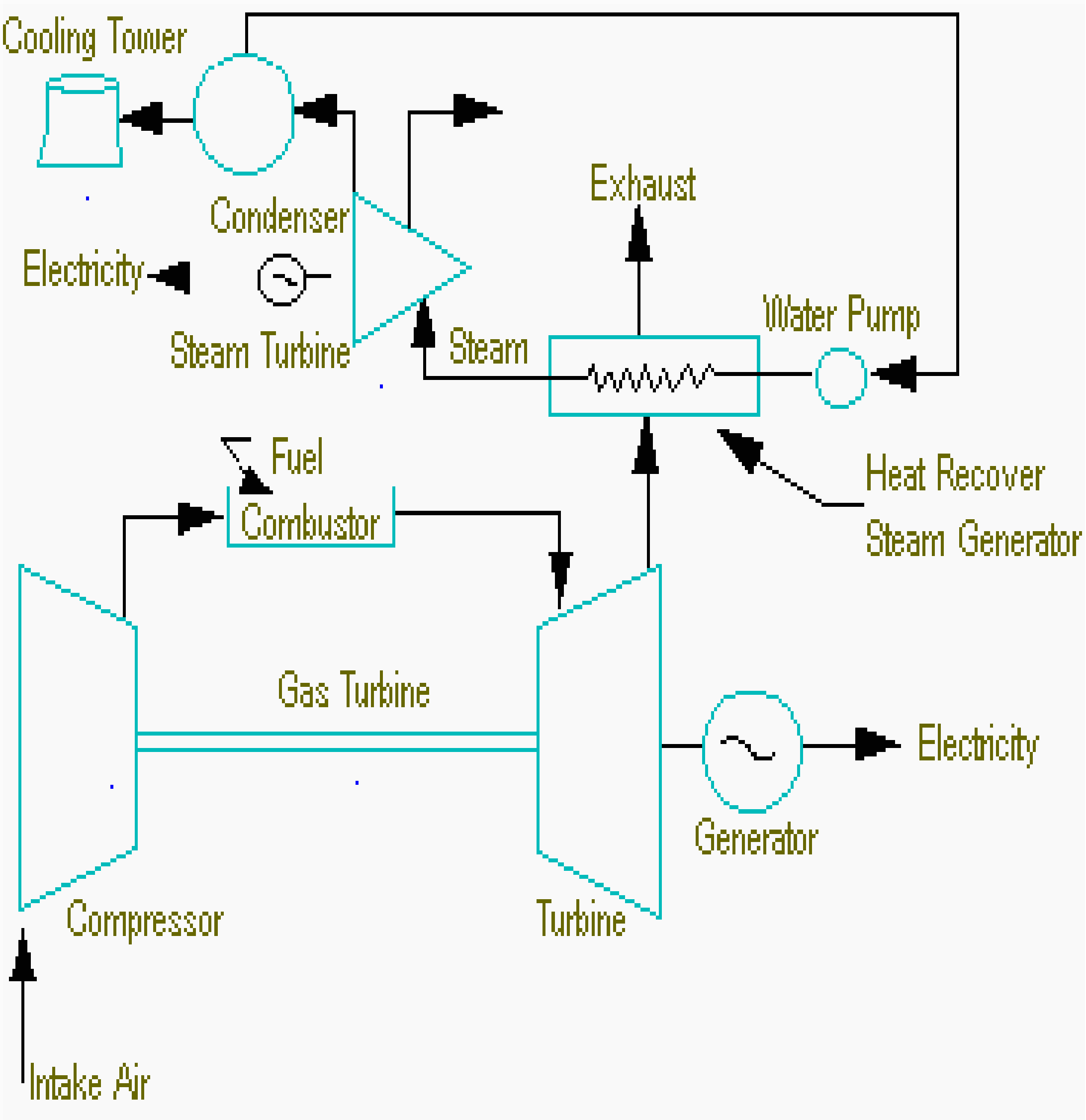
Combined cycle power plant

- Combined cycle plants use less fuel per kWh and produce fewer emissions than conventional thermal power plants.
- The turbines used in Combined Cycle Plants are more versatile than coal or oil and can be used in 90% of energy applications. Combined cycle plants are usually powered by natural gas, although fuel oil, synthesis gas or other fuels can be used.

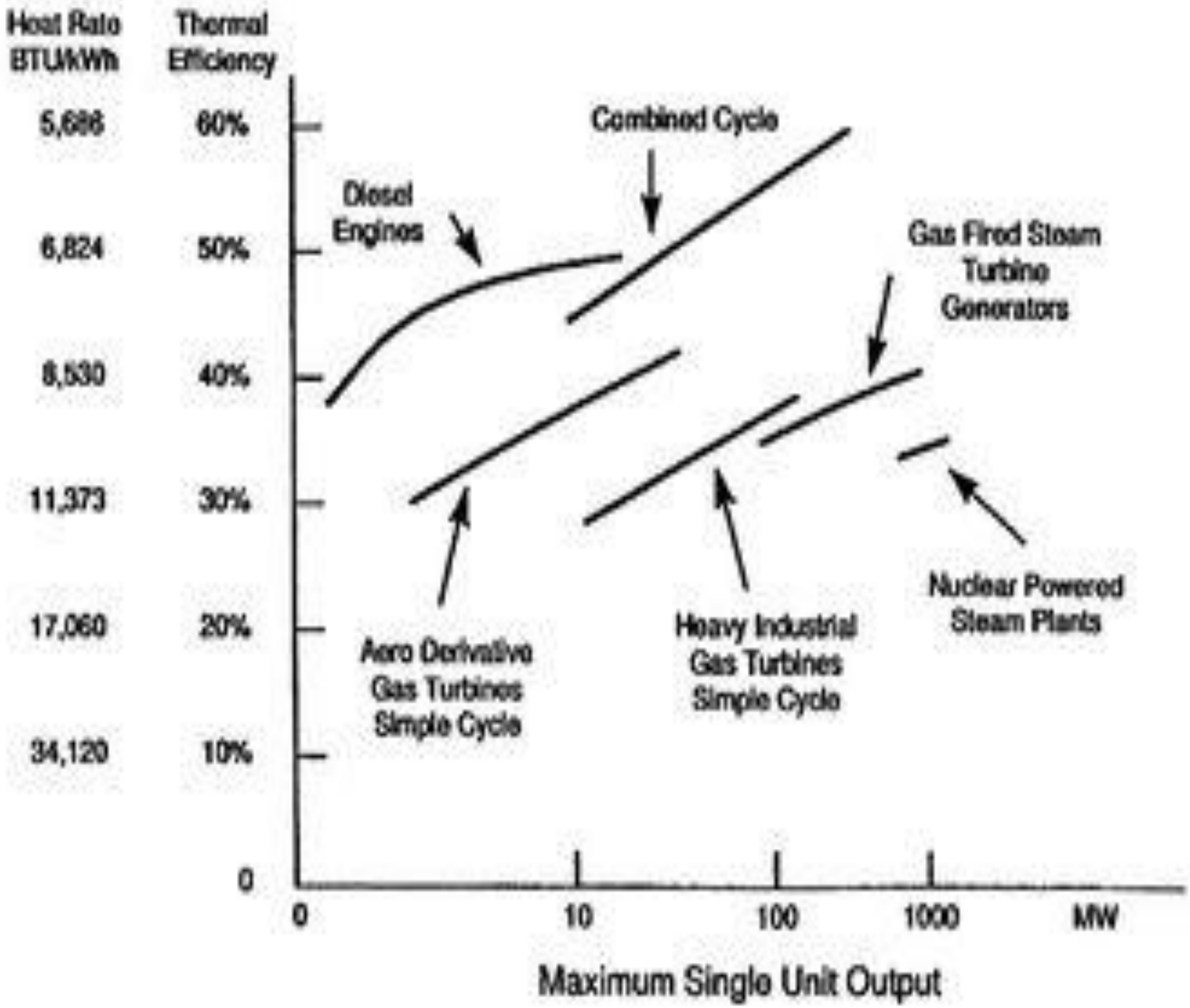
Combined cycle gas turbine

Most common combined cycle = Brayton + Rankine

Efficiency ≈ 60%



Comparison of efficiency and power output of various power products



Efficiency

- The combined efficiency of the conventional and topping unit is given as:

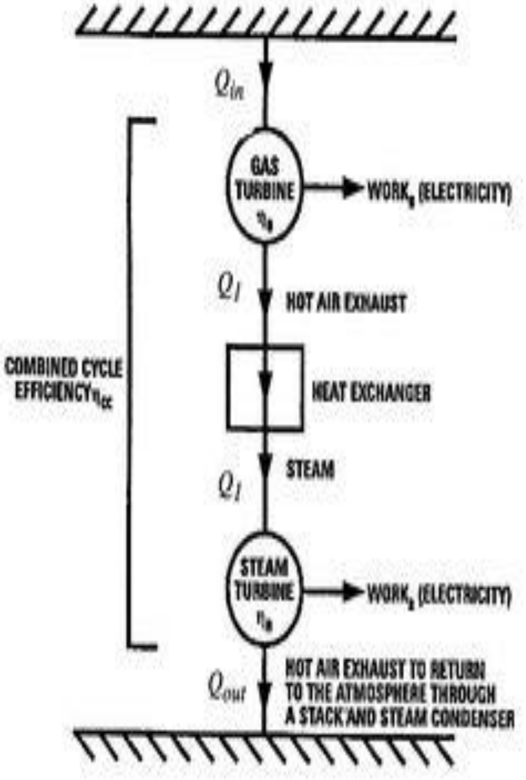
$\eta = \eta p + (1-\eta p)\, \eta o$

Where

ηp = topping unit efficiency

ηo = conventional unit efficiency

η = combined efficiency



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Magneto-hydrodynamic Power (MHD)

- In fossil-fuel steam power plant, electricity generation is accomplished in three steps:
    1. Conversion of chemical energy (of the fuel) to thermal energy via the combustion process.
    2. Conversion of thermal energy (in the steam) to mechanical energy in the turbine.
    3. Conversion of the mechanical energy into electrical energy by the electrical generator.
- Meanwhile the MHD power generator converts the thermal energy produced by the combustion into electrical energy eliminating the mechanical energy step.

MHD as topping device

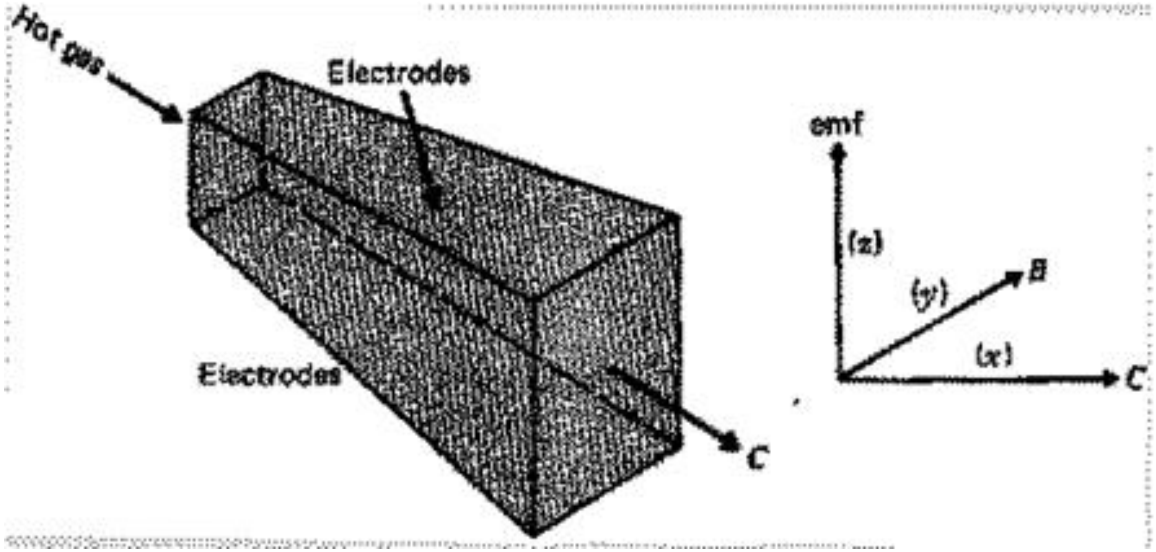
- MHD operates at a high temperature in the range of 2000-3000 ºC, thus it provides a mean to improve the performance of available power plants when operating as a topping device.
- MHD can be used as a topping unit in combination with conventional steam power generation systems. It does not use any part of the temperature range of the conventional plants,
- hence it improves the overall cycle efficiency at the expense of some increase in the initial cost.

Operation Principle of MHD generator

- The principle of the MHD generator is an old one discussed by Faraday. The interest in the MHD is however intensifying recently. A 1000 MW open cycle MHD/steam cycle is completed in USA in 1990.
- Conventional electric generators operate by moving a conductor through a magnetic field. Meanwhile the MHD generator operates by moving a charge (ionized gas) through a magnetic field.
- The induced emf caused a current to flow in the conductor, whether solid or gas, and in the external circuit.

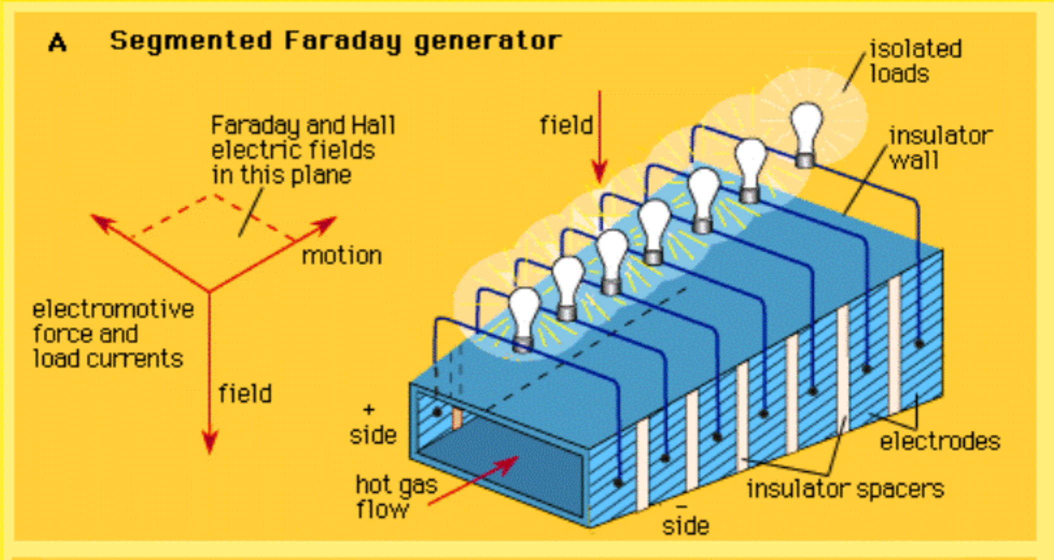
Operation Principle of MHD generator

- MHD generator consists of a divergent duct, where electrodes are placed upper and lower the channel. Field coils are installed outside the electrodes. Channel walls are cooled to protect the structure material from the high temperature



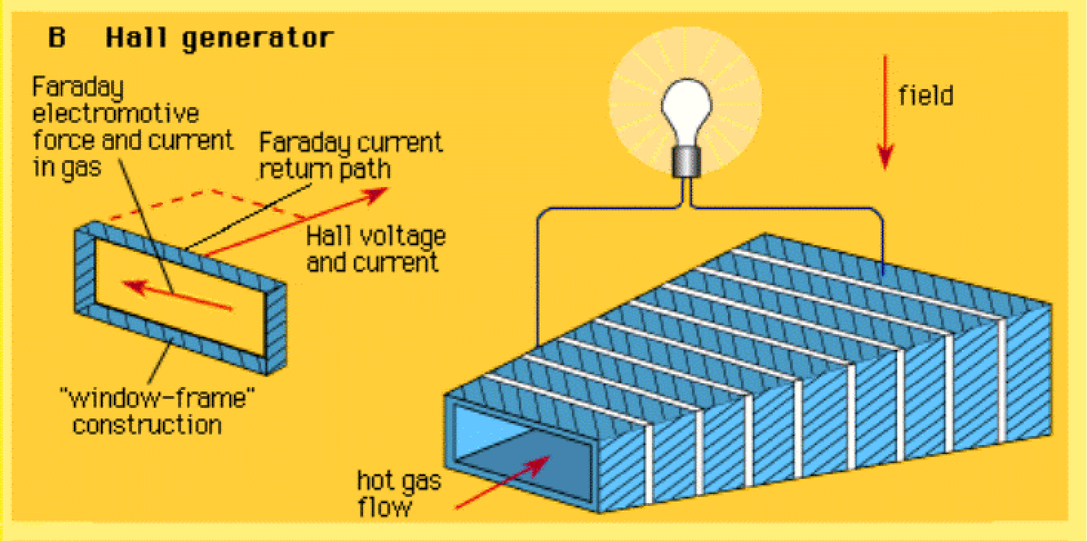
Operation Principle of MHD generator

- Hot electrically conducting gas expands in the divergent duct, this ionized gas moves (x-direction) perpendicular to magnetic field in (y-direction).
- The interaction of the moving gas with the magnetic field produces an induced electromagnetic field emf in the z-direction.
- Then the current flows from lower electrode to the upper electrode through the gas.



Hall's Effect

- The current flowing through the gas J creates an induced field that interacts with the applied field B creating a retarding force (in x-direction), which is encountered, by the force of the expanding gas through the duct (in x-direction) and this retarding force is equal to (JxB).
- The retarding force is called Hall's Effect, which produced axial emf.



Electrical conductivity

- Electrical conductivity of the working fluid in MHD generator has to be large enough.
- Such conductivity is achieved by thermal ionization of the combustion gases at high temperature since the conductivity is strongly dependent on the temperature.
- Electrical conductivity of gases is enhanced by the addition of small amounts of easily ionized impurities called “seed” such as a cesium and potassium and their compounds (KOH, K2CO3,……).

Producing very hot gases (above 2000 K)

- Oxygen combustion: produces a flame temperature of 3000K but the cost of producing oxygen consumes 9% of the energy liberated from its combustion, hence MHD efficiency may not exceed 20%.
- Air preheating: air preheating to 1000K is needed to obtain air combustion temperature of 2000K, then one should face the problem of preheating to 1000Kwhich can not be done with conventional heat exchanger.
- Enriched air combustion: one have to lower the N2 content of the air to the ratio N2/O2 = 2. The mounting of 47% of additional oxygen for enrichment has to be supplied by an air separation plant.

MHD generator analysis

- Induced electrical potential E_{ind} is given as:

  $E_{ind} = C \times B$
- since (C&B are perpendicular) then:

  $E_{ind} = C\,B$ in V/m

  Where C: speed of gas (m/s)

  B: magnetic fluid ($V.s/m^2$)
- OR total voltage

  $V_{total} = z\,E_{ind} = z\,CB$

  Where z is the separation between electrodes.

Current density

- Current density $J = i/A = \Delta V_{int} / ARg$

  ΔV_{int} internal voltage drop,

  A area of electrodes,

  Rg internal resistance.

- Or

  $J = i/A = \Delta V_{int} / ARg = \Delta V_{int}\, \sigma / z$

  Where σ: gas electrical conductivity ohm^{-1}/m

Current density

- Let $n = Re / (Re + Rg)$; Re: external resistance.
- External voltage drop per meter separation is related to the induced emf as

  $E = n E_{ind}$

Recall $J = \Delta V_{int}\, \sigma / z$, $\Delta V_{int} = Jz / \sigma$

- However $\Delta V_{int} = (E_{ind} – E)z = z$ (total emf - external emf drop)
- Then $J = [(E_{ind} – E)\, z]\, \sigma / z = (E_{ind} – E)\, \sigma = (E_{ind} – n\, E_{ind})\sigma = \sigma\, E_{ind}(1 – n)$
- Recall $E_{ind} = CB$
- Now $J = \sigma CB(1 - n)$; amper/m^2

Generated power

- Generated power:

  W = external drop * current

  $W = \Delta V_{ext} i = \Delta V_{ext} JA = \Delta V_{ext} J(xy)$
- But $\Delta V_{ext} = Ez = nE_{ind}z = nCBz$
- Now: $W = \Delta V_{ext} J(xy) = nCBJ(zxy)$
- Sub. for J

  $W = nCB[\sigma CB(1 - n)](xyz)$

  $W = \sigma nC^2B^2(1 - n)v$

  Where v: volume of duct,

  Usually , $0.7 < n < 0.9$

Length of duct

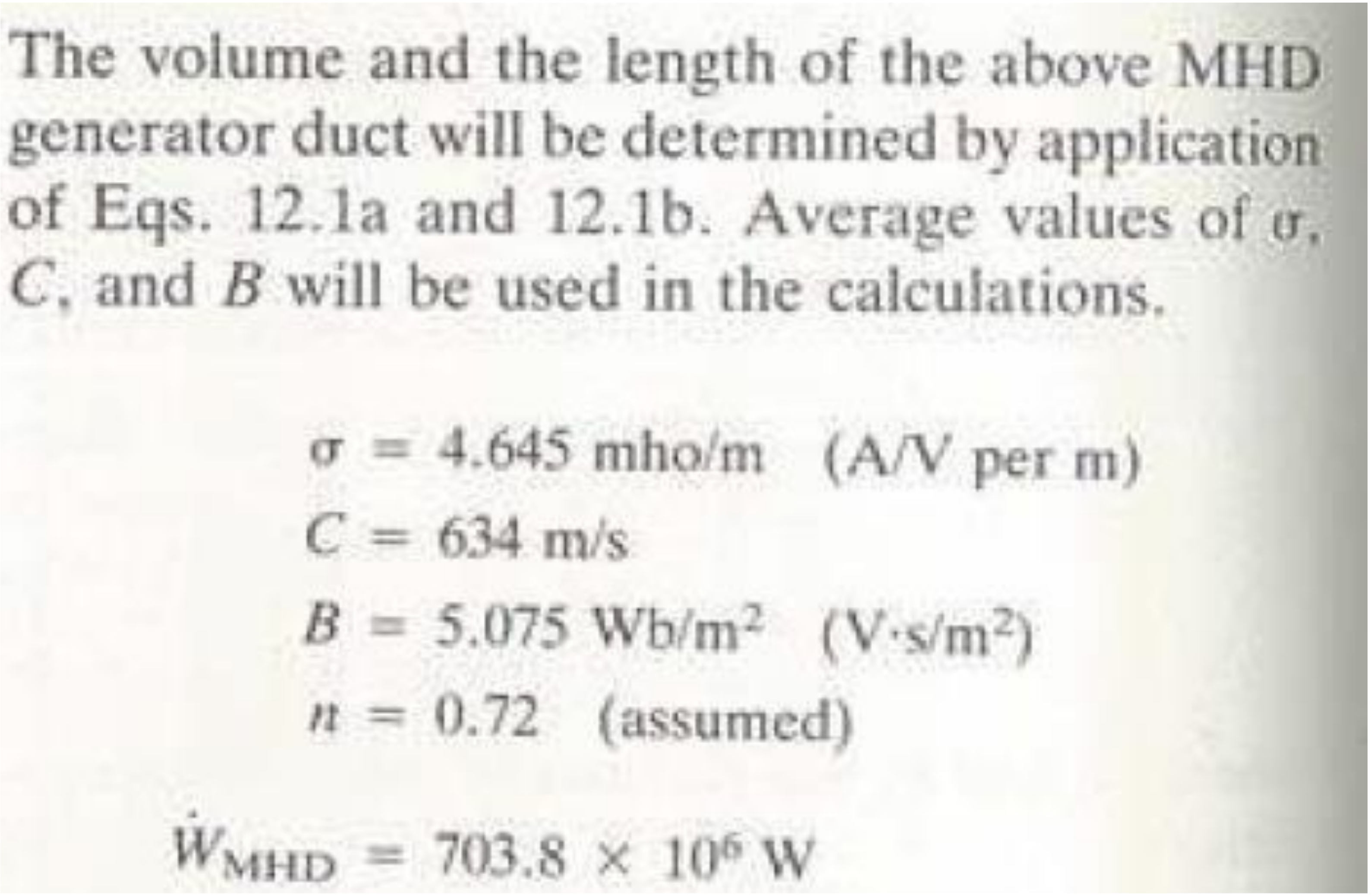
- From fluid mechanics, the retarding force is equal to pressure drop per unit length.
- Retarding force = $-JB = dP/dx$ (see Hall's effect)

  And $dx = -dP/JB$
- Sub. for $J = \sigma CB(1 - n)$

  $dx = -dP/[\sigma CB^2(1 - n)$
- Integrating

  $x_2 - x_1 = L = (P_1 - P_2) / \sigma CB^2(1 - n)$

e.g. 12-1 p416 Sorenson



The volume and the length of the above MHD generator duct will be determined by application of Eqs. 12.1a and 12.1b. Average values of σ, C, and B will be used in the calculations.

$$\sigma = 4.645 \text{ mho/m} \quad (\text{A/V per m})$$

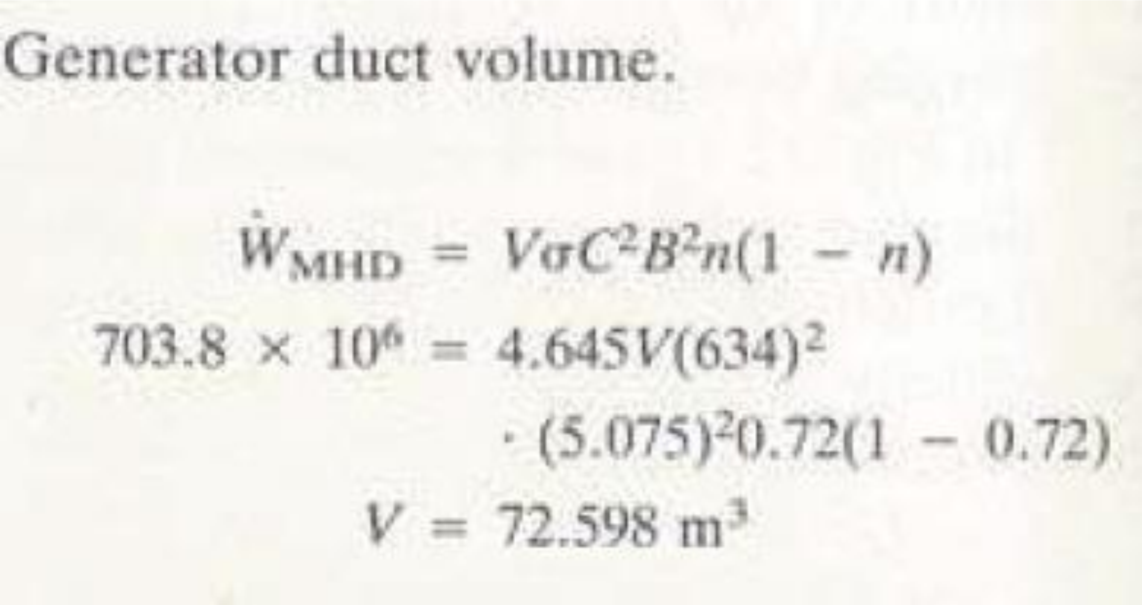
$$C = 634 \text{ m/s}$$

$$B = 5.075 \text{ Wb/m}^2 \quad (\text{V}\cdot\text{s/m}^2)$$

$$n = 0.72 \quad (\text{assumed})$$

$$\dot{W}_{\text{MHD}} = 703.8 \times 10^6 \text{ W}$$

e.g. 12-1 p416 Sorenson

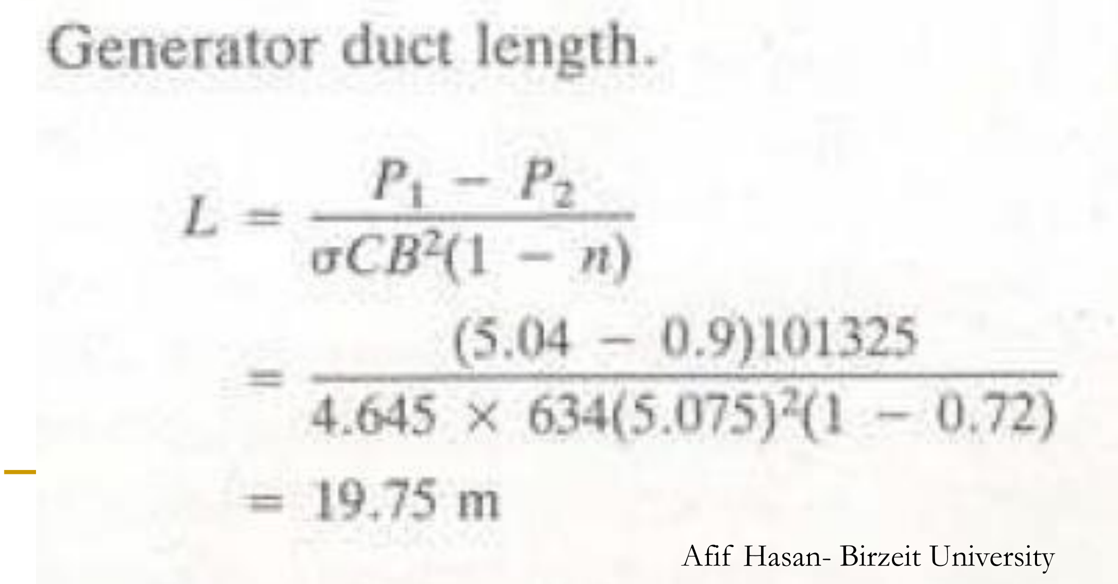


Generator duct volume.

$$\dot{W}_{\mathrm{MHD}} = V\sigma C^2 B^2 n(1 - n)$$

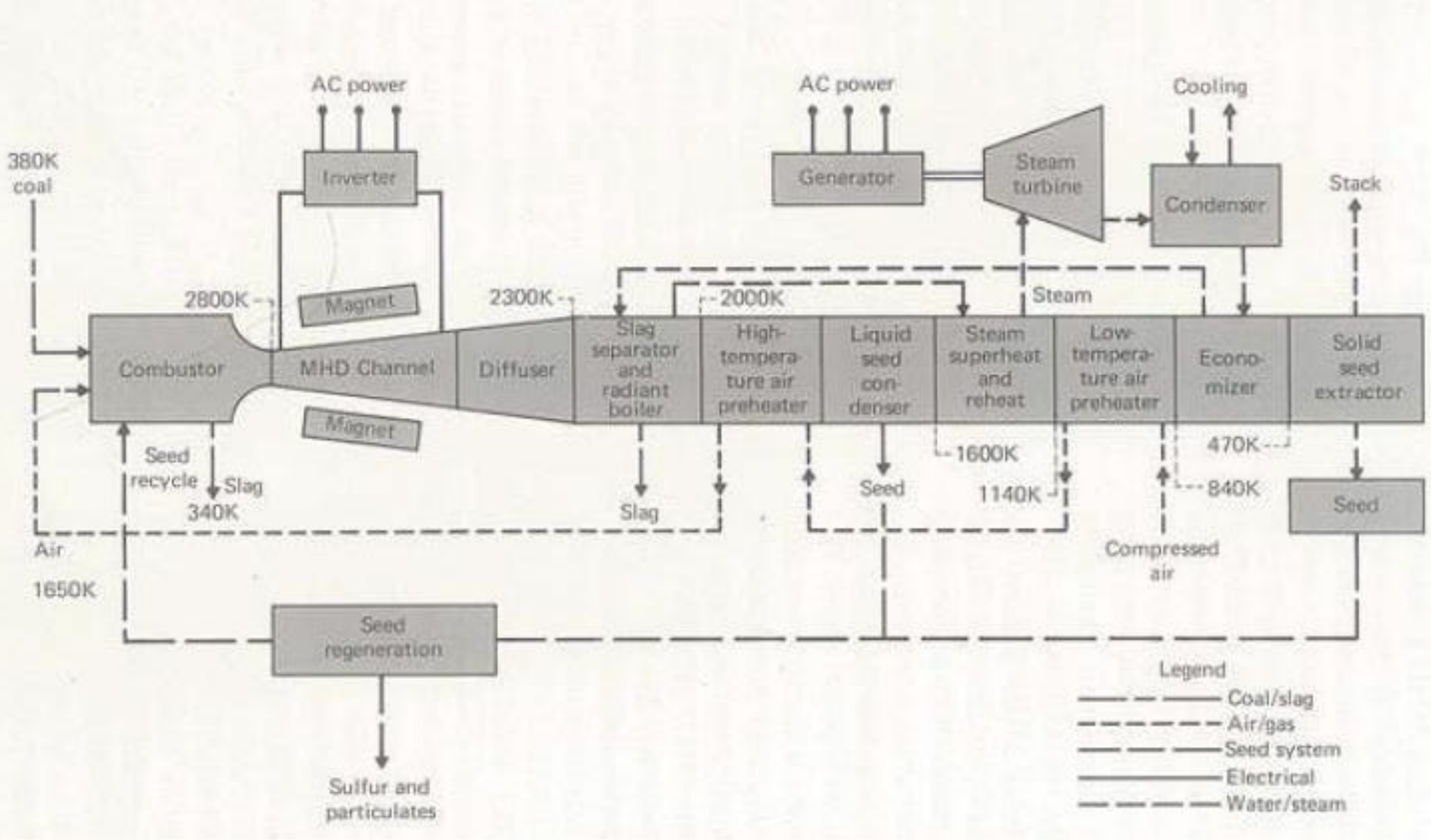
$$703.8 \times 10^6 = 4.645V(634)^2 \cdot (5.075)^2 0.72(1 - 0.72)$$

$$V = 72.598 \text{ m}^3$$



Generator duct length.

$$L = \frac{P_1 - P_2}{\sigma C B^2(1 - n)} = \frac{(5.04 - 0.9)101325}{4.645 \times 634(5.075)^2(1 - 0.72)} = 19.75 \text{ m}$$


380K
coal
AC power
Inverter
Magnet
Magnet
2800K
Combustor
MHD Channel
Diffuser
2300K
Slag separator and radiant boiler
2000K
High-temperature air preheater
Liquid seed condenser
Steam superheat and reheat
Low-temperature air preheater
Economizer
Solid seed extractor
AC power
Generator
Steam turbine
Cooling
Condenser
Stack
Steam
Seed recycle
Slag
340K
Slag
Seed
1600K
1140K
470K
840K
Compressed air
Seed
Air
1650K
Seed regeneration
Sulfur and particulates
Legend
Coal/slag
Air/gas
Seed system
Electrical
Water/steam

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Thermoelectric Power

- If one end of the thermoelectric material is heated, the electrons-negative charge- moves to the cold end as a result of the increasing kinetic energy, leaving the positive charge (holes) in the crystal.
- This effect is known as Seebeck or thermoelectric effect.
- An electric voltage difference is developed between the cold and hot ends.
- If an external load is provided, an electric current will flow.

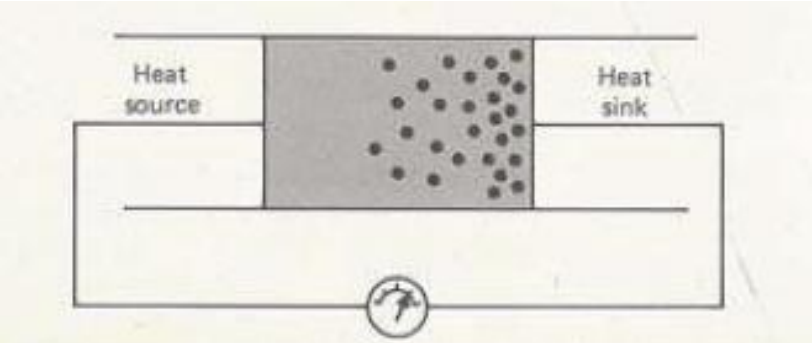
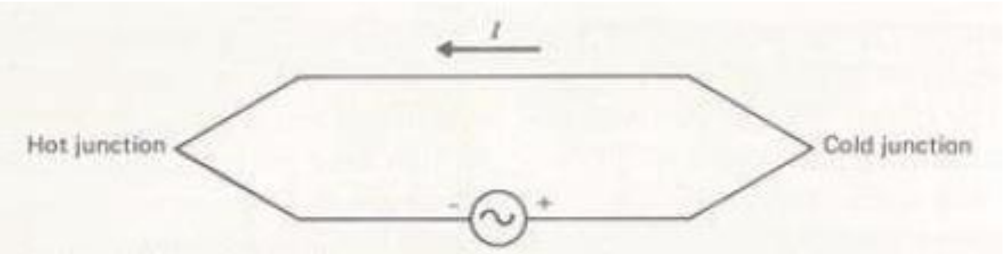


Figure 12.6 Electron concentration in a thermoelectric material.



Thermoelectric materials

- Insulators develop 10,000 μV/K but they cannot serve as thermoelectric materials since they have high electrical resistivity (low current and little power is generated).
- On the other hand, metals have a higher density of free electrons and produce a low Seebeck voltage of about 5 μV/K, but they have an extremely low internal resistance (so high current). The combination of low voltage and high current however results in little power output.
- A good thermoelectric material would have conductivity and Seebeck voltage characteristics between those of insulators and those of metals.

Thermoelectric materials

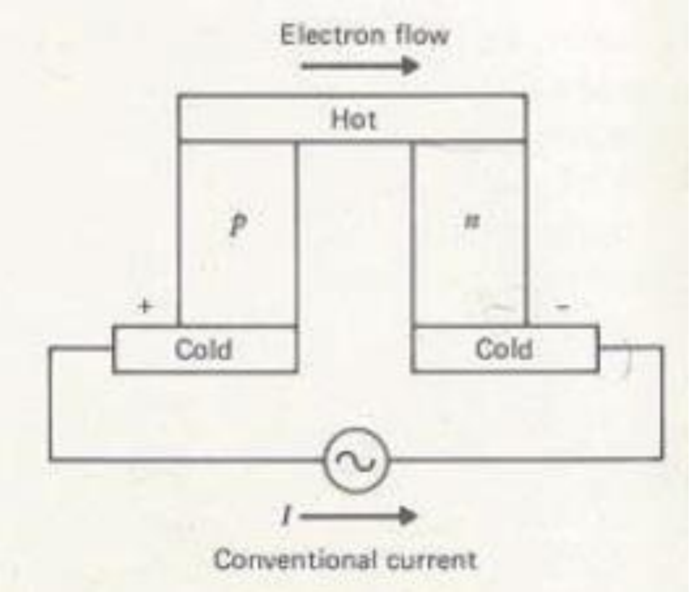
- Properties in order to develop a high emf:
  - Low density of free electrons, hence the output voltage is inversely proportional to the number of the free electrons. On contrary, the conductivity is directly proportional to the number of free electrons. The optimum free electron density is 10^{19} electrons/cm^3 developing 175 μV/K.
  - Low electrical resistivity or high electrical conductivity.
  - Low thermal conductivity in order to reduce the amount of wasted energy by conduction through the thermoelectric material between the cold and hot ends.

semiconductors

- The above requirements are fulfilled by semiconductors since they have low electrical and thermal conductivity. Examples of semiconducting materials are lead telluride PbTe and GeSi.
- In the n-type semiconductor, the lattice has a small excess of negative charge, while in the p-type, the lattice has a deficiency of electrons creating “holes” that are free to move and provide the effect of positively charged particles.
- If the lattice contains no charge carriers or an equal number of positive and negative carriers, the semiconductor is classified as intrinsic.

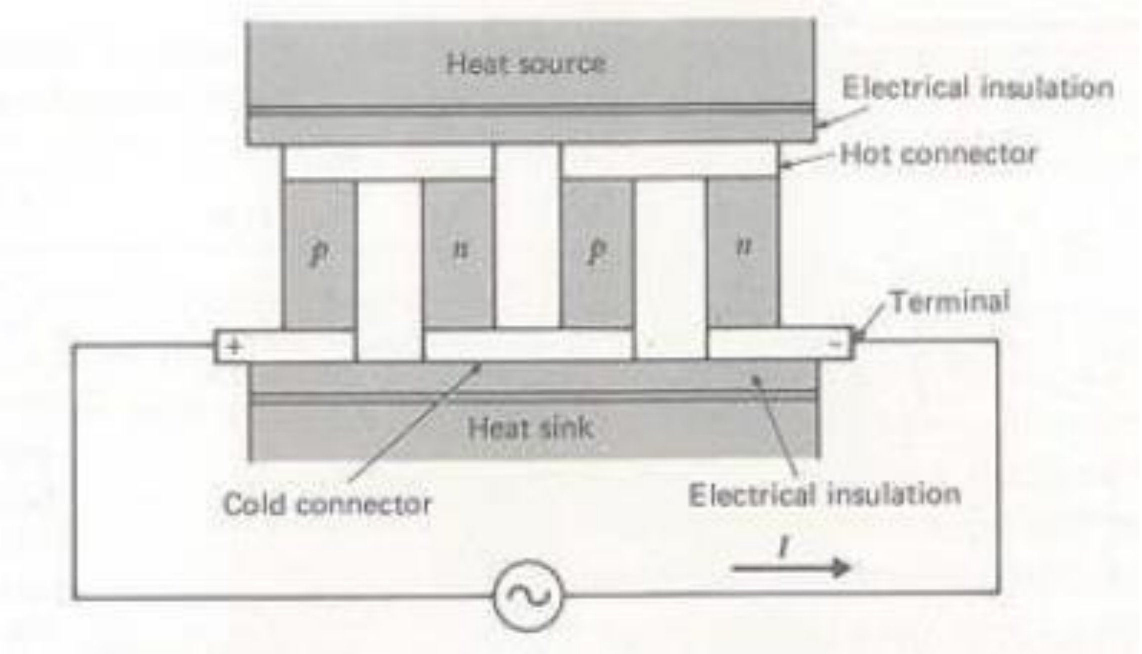
Semiconductors convertor

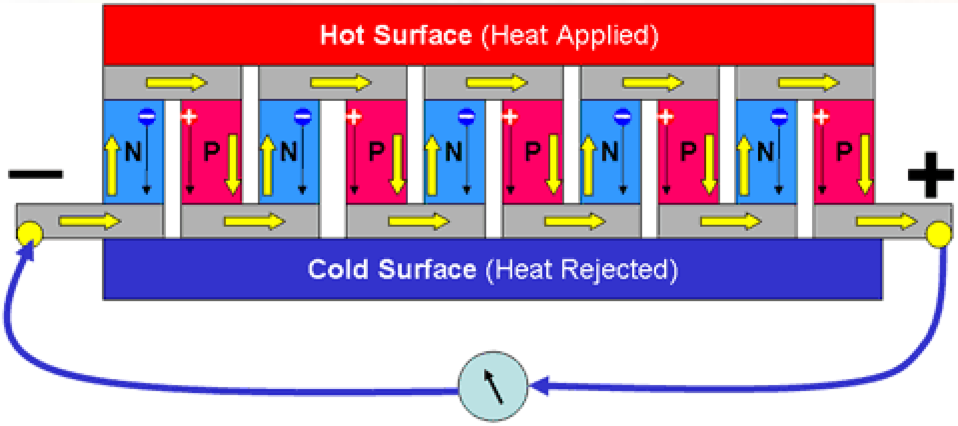
- When the n-type and p-type semiconductors are combined as shown in the figure, both the positive and negative terminals are cold-side conductors to prevent the heat leakage through the external circuit. The direction of the electron flow and the conventional current are shown



Thermoelectric power generator

- The p-type and n-type semiconductors are arranged alternately in order to produce a higher voltage (the voltage is additive) as shown in the following graph.





Thermoelectric Generator (TEG)

Performance of thermoelectric generator

- Consider hot junction at TH, K

  Cold Junction at TL, K.
- Then the open circuit voltage V,:

  V = S(TH – TL)

  S: Seeback coefficient.
- Let σ: electrical conductivity Ω-1/m

  k: thermal conductivity W/K.m

Then define: $Z = s^2\sigma/k$ where Z is figure of merit.

For a junction formed from two materials 1 & 2

$$Z = \frac{(s1+s2)^2}{\left[\sqrt{k1/\sigma1}+\sqrt{k2/\sigma2}\right]^2}$$

Power output for generator

- Power output for generator, W

$W = I^2R$ but $I = V / R_{tot} =$

$I = S(T_H - T_L) / R_{tot} = S\,\Delta T / R_{tot}$

- For maximum power; $R_{ext} = R_{inter} = R$

$I = S\,\Delta T / 2R \rightarrow W = S^2(\Delta T)^2 / 4R$

- Let $R = \rho L/A$ ρ in $\Omega.m$
- Then $W = S^2(\Delta T)^2 A/ 4\rho L$

Or $W = AS^2(\Delta T)^2 / 4\rho L$ L: length of element

Efficiency of thermoelectric converter

- Large amount of energy is lost because of conduction through the thermoelectric material; from hot to cold junction (90% of energy is lost by conduction).
- Hence a low overall efficiency of about 5% is obtained.
- Thermoelectric system has a low power capability (1 kW) with a high capital cost. The main advantage of this converter is the absence of moving parts

Efficiency of thermoelectric converter

- Defining conversion efficiency as η = electrical output / Heat input from source
- $\eta = I^2Rext / Q_H$
- The maximum conversion efficiency ηmc is given as,
- $$\eta mc = \eta c \frac{\sqrt{1+Z\overline{\overline{T}}}-1}{\sqrt{1+Z\overline{\overline{T}}}+Tc/Th}$$

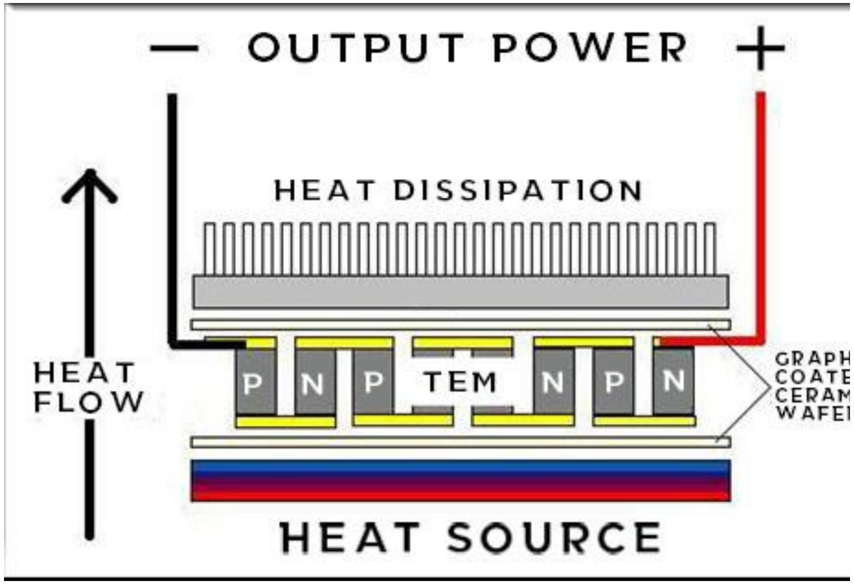
  Where $T = (T_H + T_L) /2$, Z = (Zcold + Zhot) / 2 ; ηc = 1-TH /TL
- Conversion efficiency at maximum power, ηmp

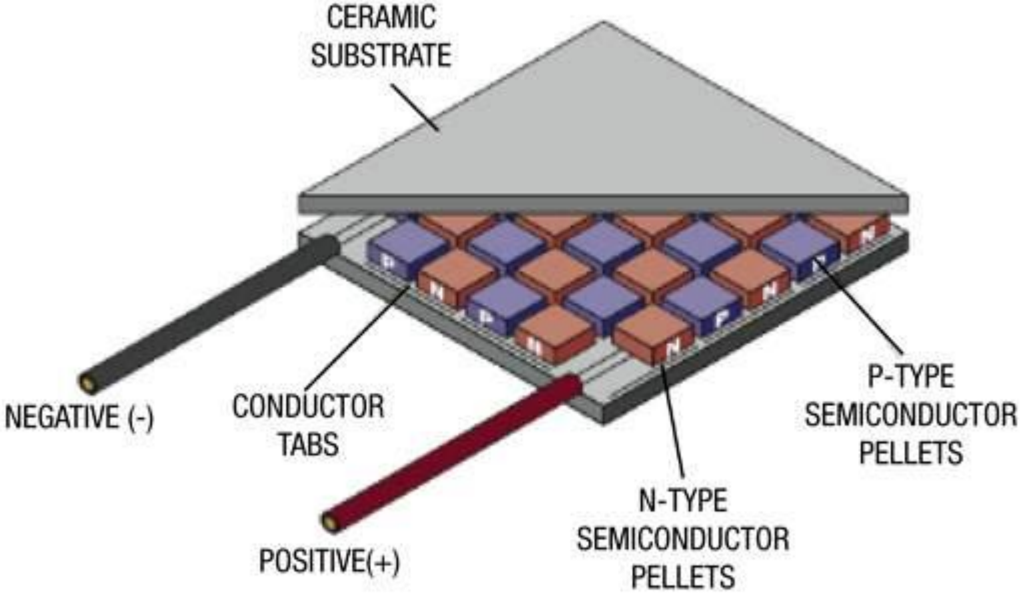
$$\eta mp = \frac{\Delta T}{Th} \frac{1}{\left[\frac{4}{ZTh}+2-\frac{\Delta T}{2Th}\right]}$$

- Note maximum power obtain when internal resistance equals external resistance.

Applications

- Space vehicles, military equipment, and service at remote areas and undersea installations.
- The commercial applications are unlikely due to low efficiency.





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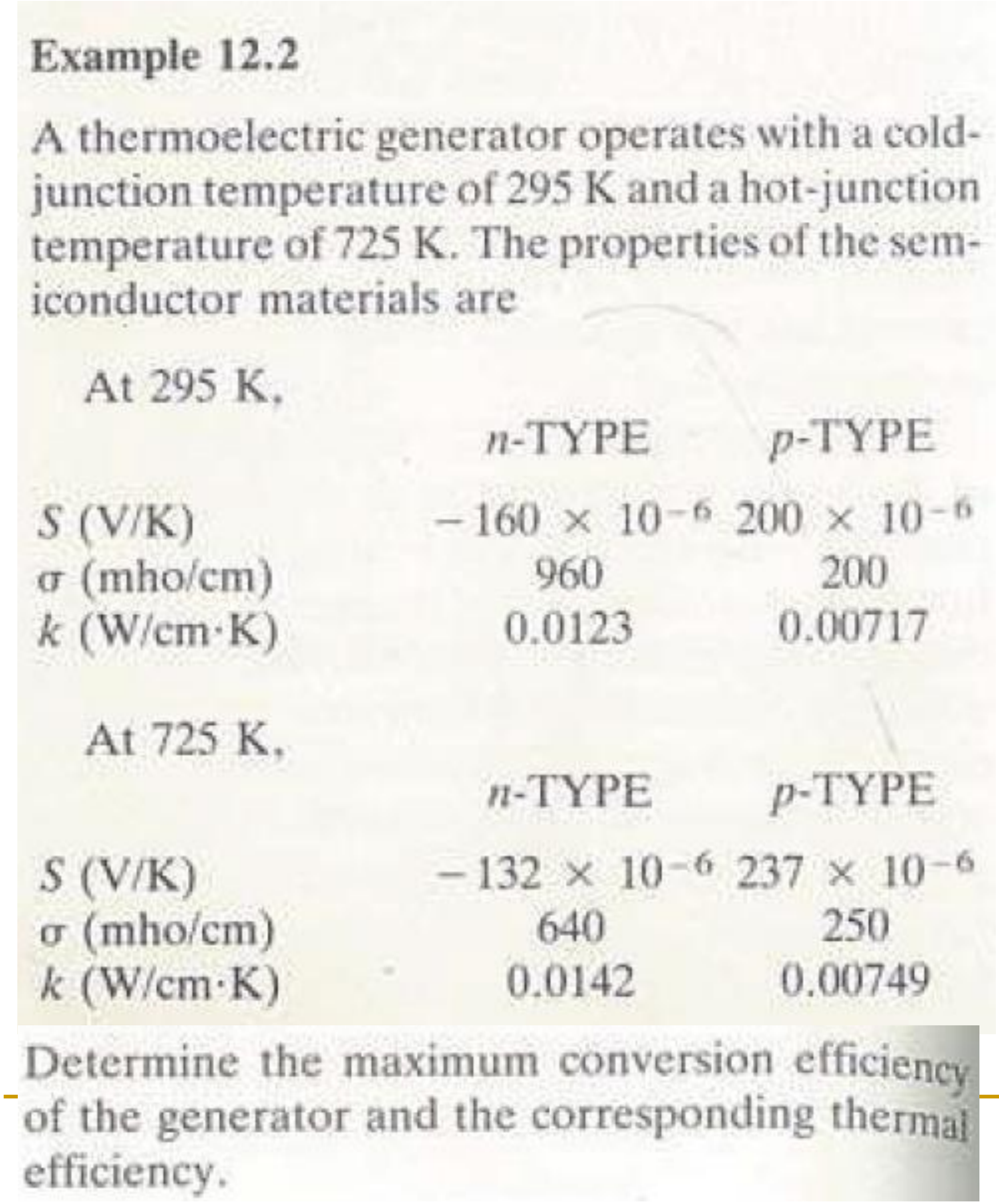


Example 12.2

A thermoelectric generator operates with a cold-junction temperature of 295 K and a hot-junction temperature of 725 K. The properties of the semiconductor materials are

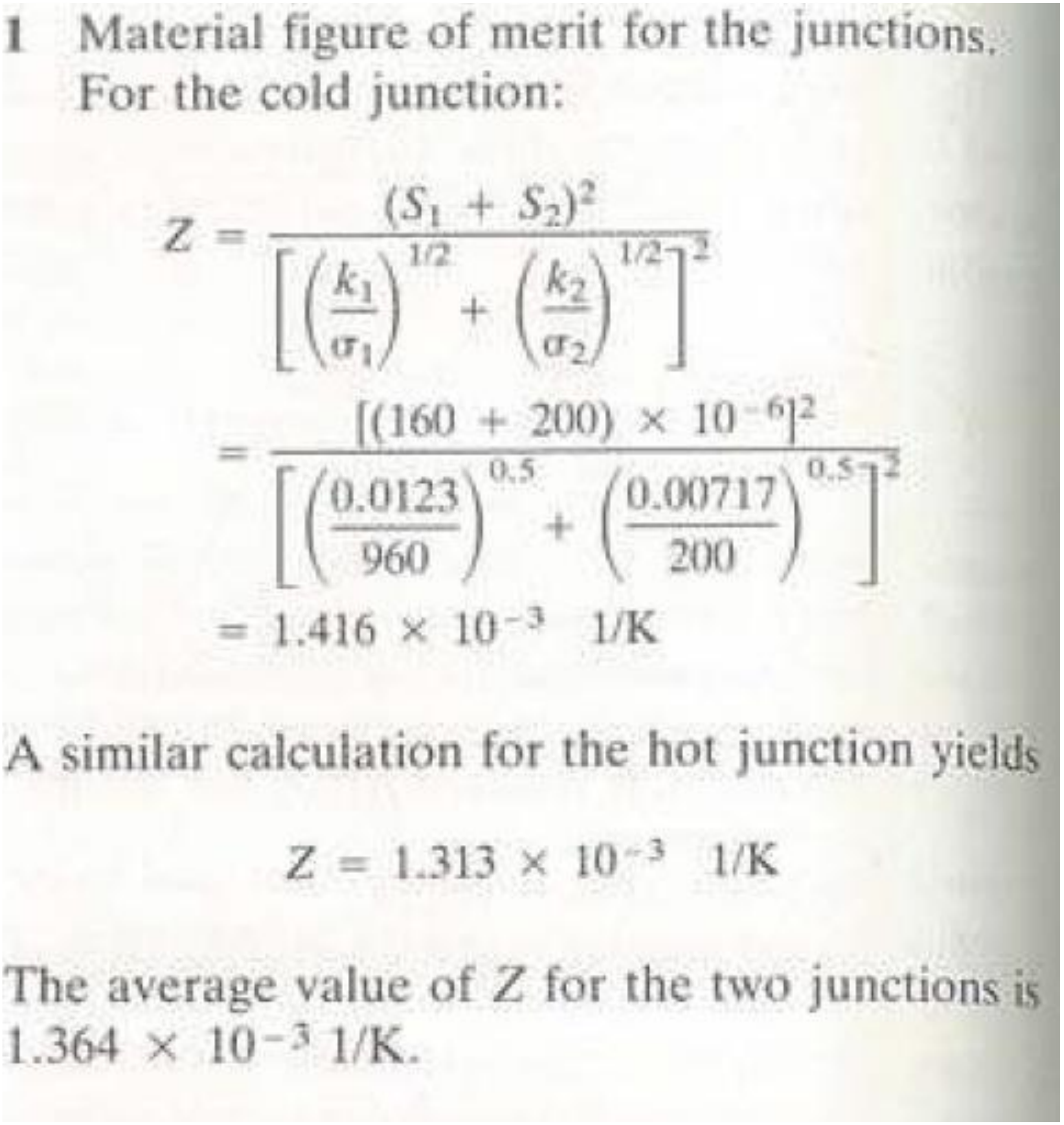
At 295 K,

	n-TYPE	p-TYPE
S (V/K)	-160×10^{-6}	200×10^{-6}
σ (mho/cm)	960	200
k (W/cm·K)	0.0123	0.00717

At 725 K,

	n-TYPE	p-TYPE
S (V/K)	-132×10^{-6}	237×10^{-6}
σ (mho/cm)	640	250
k (W/cm·K)	0.0142	0.00749

Determine the maximum conversion efficiency of the generator and the corresponding thermal efficiency.



1 Material figure of merit for the junctions.
For the cold junction:

$$Z = \frac{(S_1 + S_2)^2}{\left[\left(\frac{k_1}{\sigma_1}\right)^{1/2} + \left(\frac{k_2}{\sigma_2}\right)^{1/2}\right]^2}$$

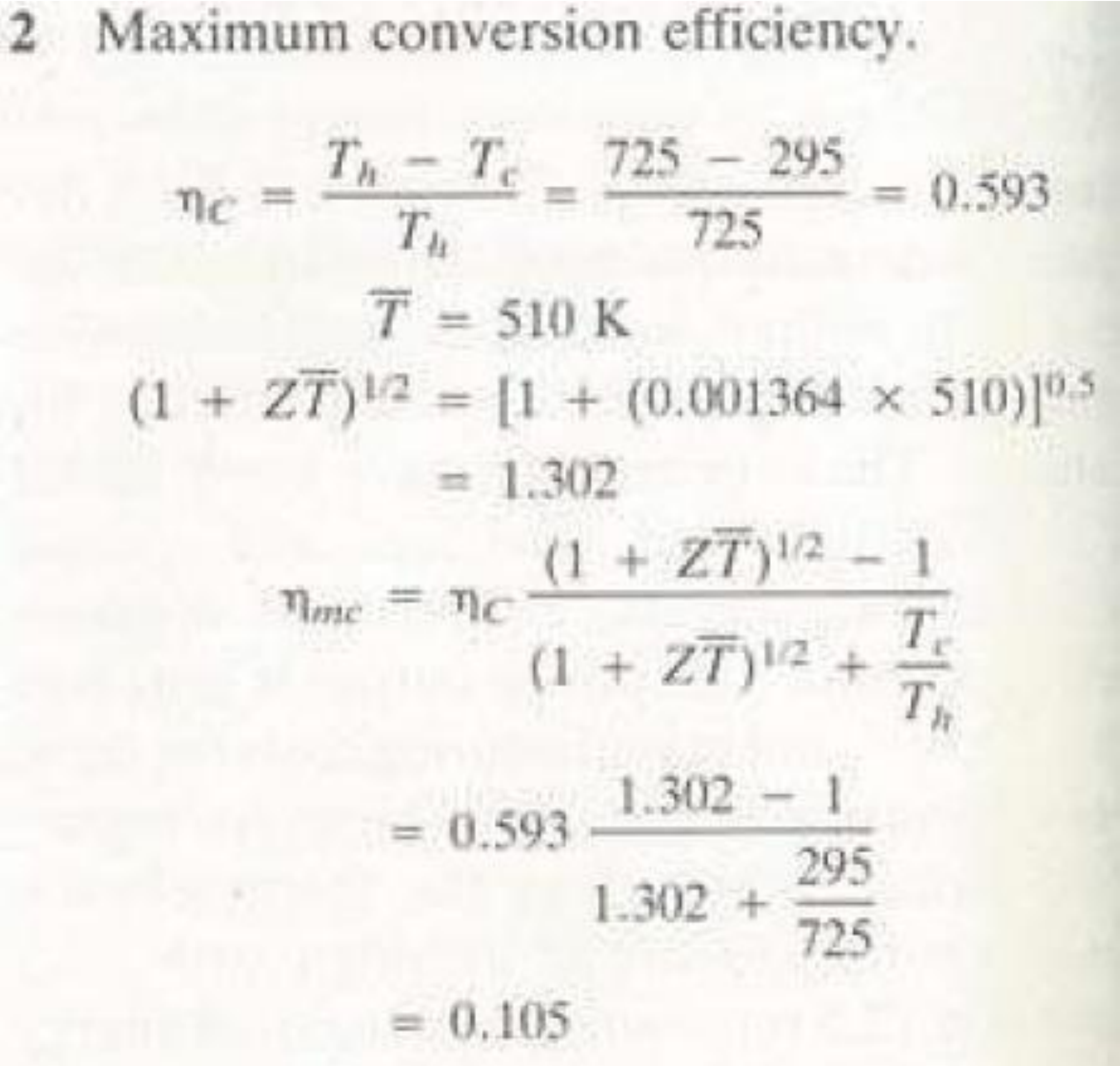
$$= \frac{[(160 + 200) \times 10^{-6}]^2}{\left[\left(\frac{0.0123}{960}\right)^{0.5} + \left(\frac{0.00717}{200}\right)^{0.5}\right]^2}$$

$$= 1.416 \times 10^{-3} \quad 1/\mathrm{K}$$

A similar calculation for the hot junction yields

$$Z = 1.313 \times 10^{-3} \quad 1/\mathrm{K}$$

The average value of Z for the two junctions is 1.364×10^{-3} 1/K.



2 Maximum conversion efficiency.

$$\eta_C = \frac{T_h - T_c}{T_h} = \frac{725 - 295}{725} = 0.593$$

$$\overline{T} = 510\ \mathrm{K}$$

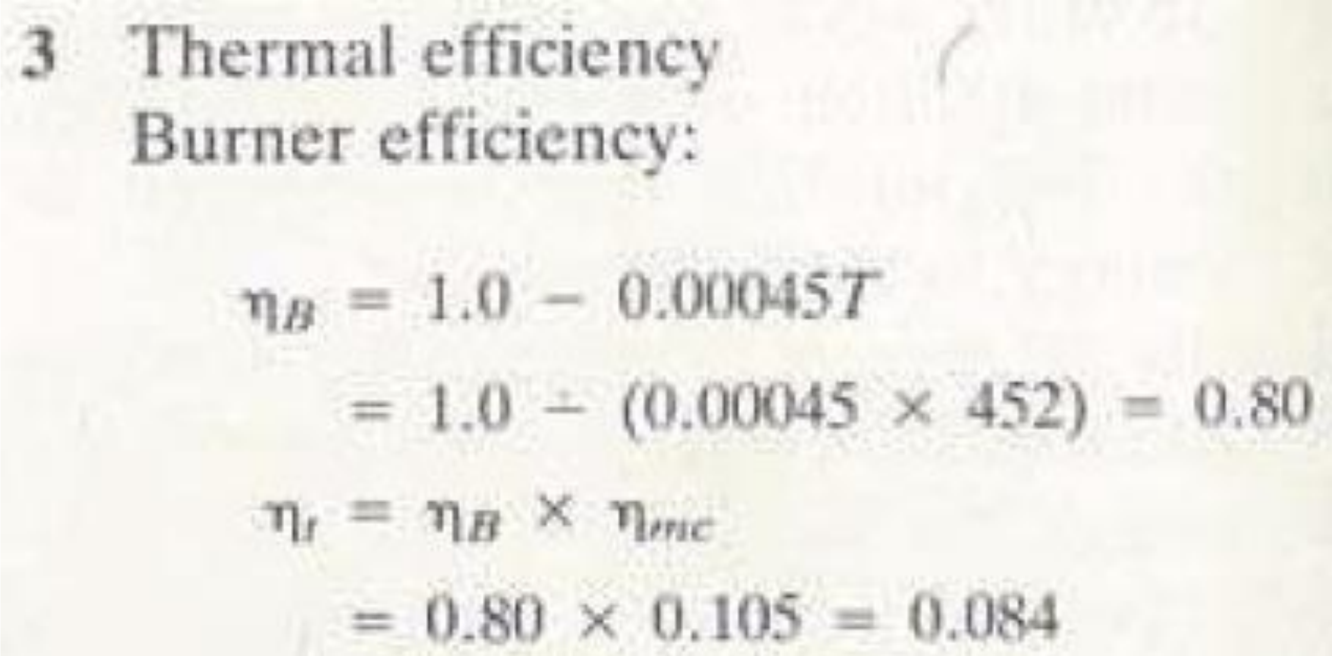
$$(1 + Z\overline{T})^{1/2} = [1 + (0.001364 \times 510)]^{0.5}$$

$$= 1.302$$

$$\eta_{mc} = \eta_C \frac{(1 + Z\overline{T})^{1/2} - 1}{(1 + Z\overline{T})^{1/2} + \dfrac{T_c}{T_h}}$$

$$= 0.593 \frac{1.302 - 1}{1.302 + \dfrac{295}{725}}$$

$$= 0.105$$



3 Thermal efficiency

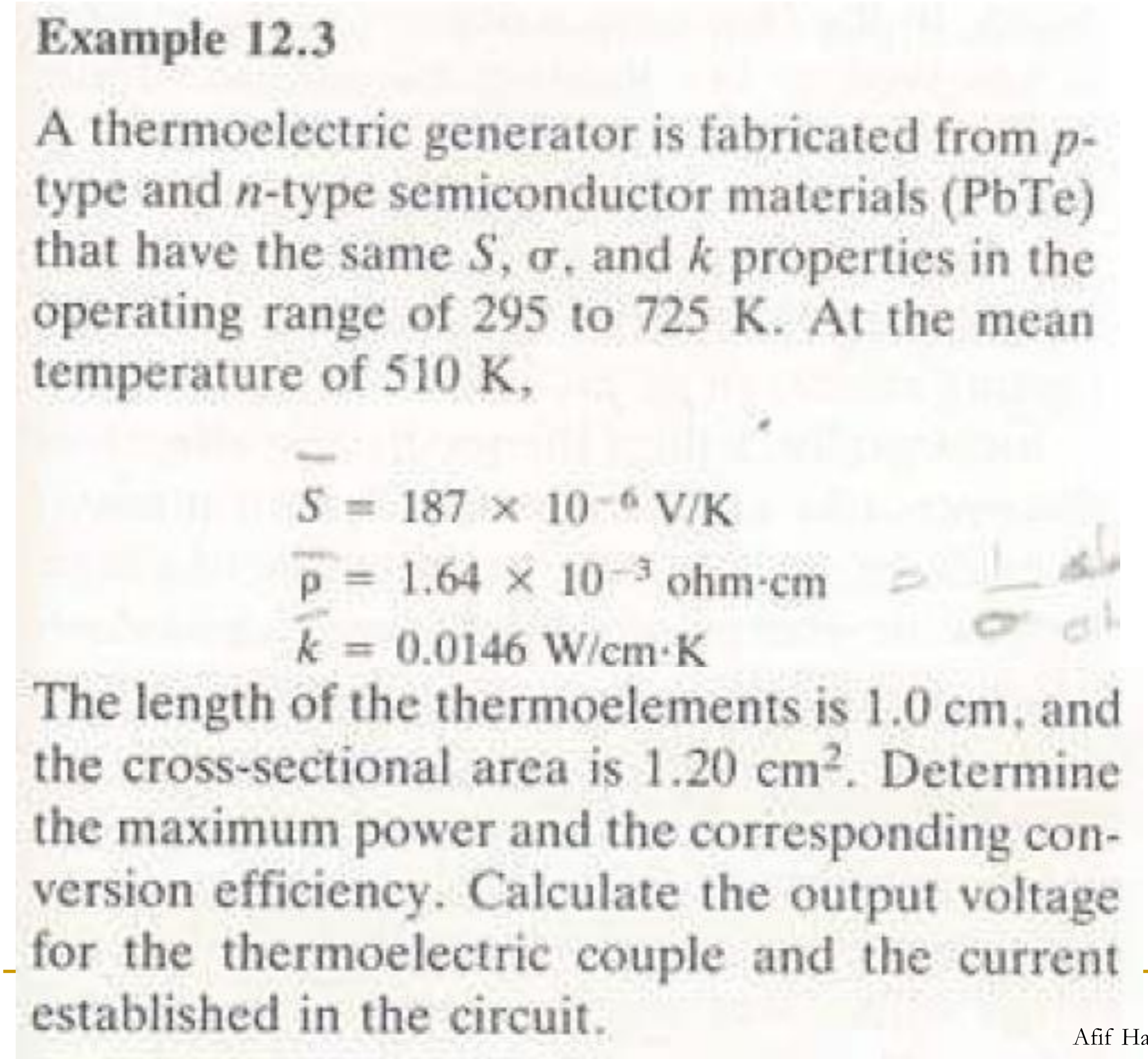
Burner efficiency:

$$\eta_B = 1.0 - 0.00045T$$

$$= 1.0 - (0.00045 \times 452) = 0.80$$

$$\eta_t = \eta_B \times \eta_{mc}$$

$$= 0.80 \times 0.105 = 0.084$$



Example 12.3

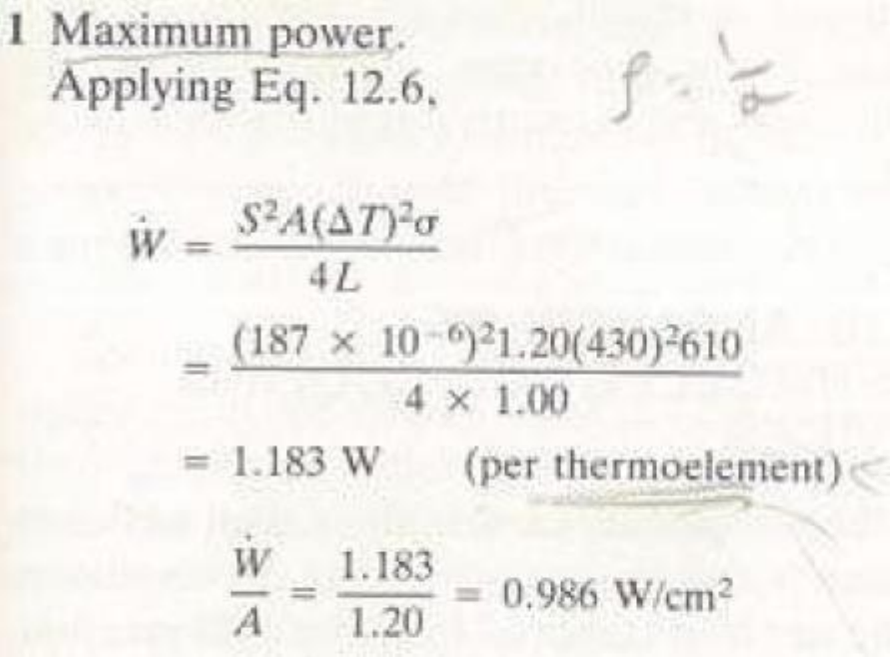
A thermoelectric generator is fabricated from *p*-type and *n*-type semiconductor materials (PbTe) that have the same S, σ, and k properties in the operating range of 295 to 725 K. At the mean temperature of 510 K,

$$\bar{S} = 187 \times 10^{-6} \text{ V/K}$$

$$\bar{\rho} = 1.64 \times 10^{-3} \text{ ohm·cm} \quad = \frac{1}{\sigma}$$

$$\bar{k} = 0.0146 \text{ W/cm·K}$$

The length of the thermoelements is 1.0 cm, and the cross-sectional area is 1.20 cm^2. Determine the maximum power and the corresponding conversion efficiency. Calculate the output voltage for the thermoelectric couple and the current established in the circuit.



1 Maximum power.

Applying Eq. 12.6,

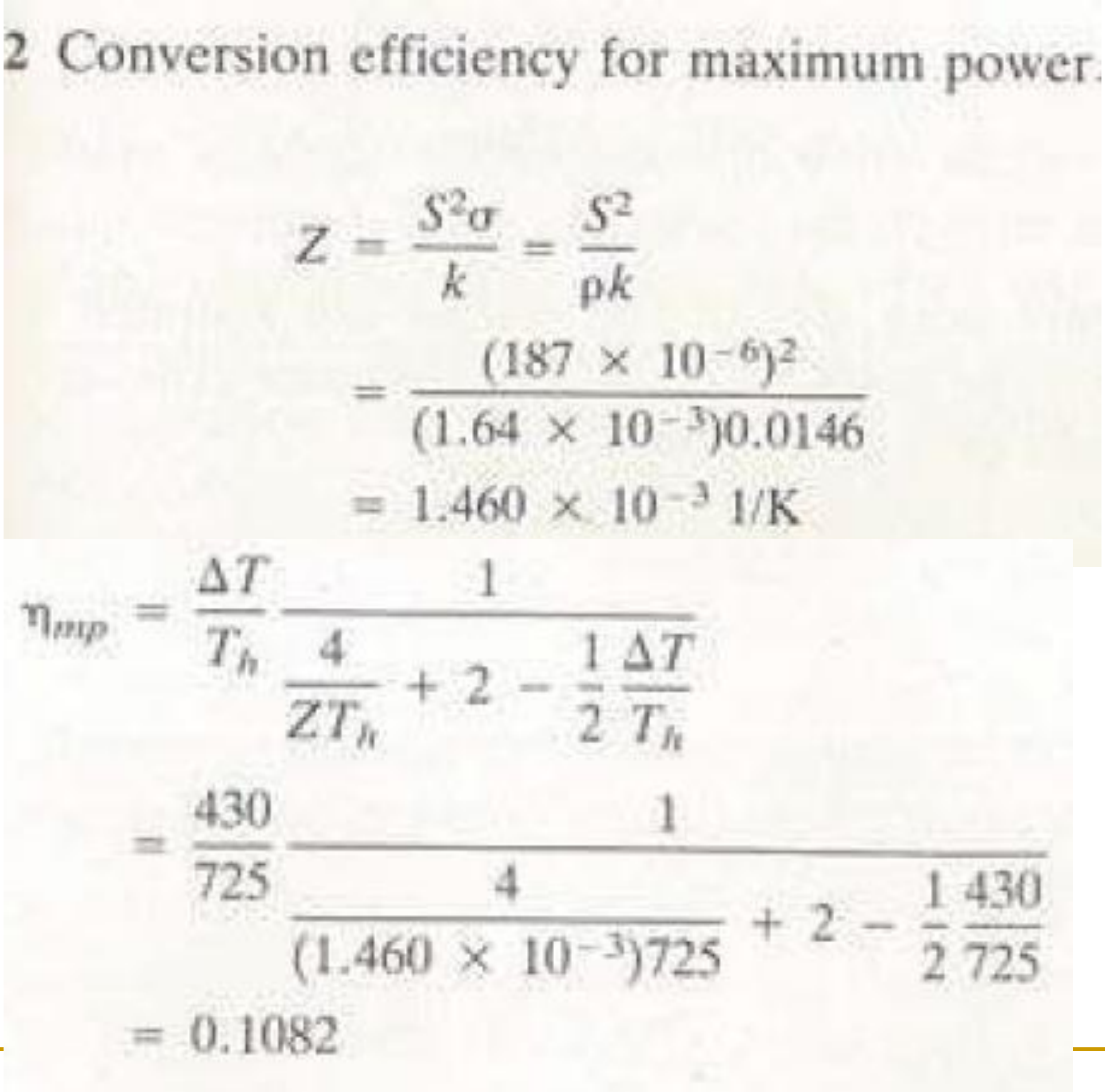
$\rho = \frac{1}{\sigma}$

$$\dot{W} = \frac{S^2 A (\Delta T)^2 \sigma}{4L}$$

$$= \frac{(187 \times 10^{-6})^2 1.20 (430)^2 610}{4 \times 1.00}$$

$$= 1.183 \text{ W} \qquad \text{(per thermoelement)}$$

$$\frac{\dot{W}}{A} = \frac{1.183}{1.20} = 0.986 \text{ W/cm}^2$$



2 Conversion efficiency for maximum power.

$$Z = \frac{S^2\sigma}{k} = \frac{S^2}{\rho k}$$

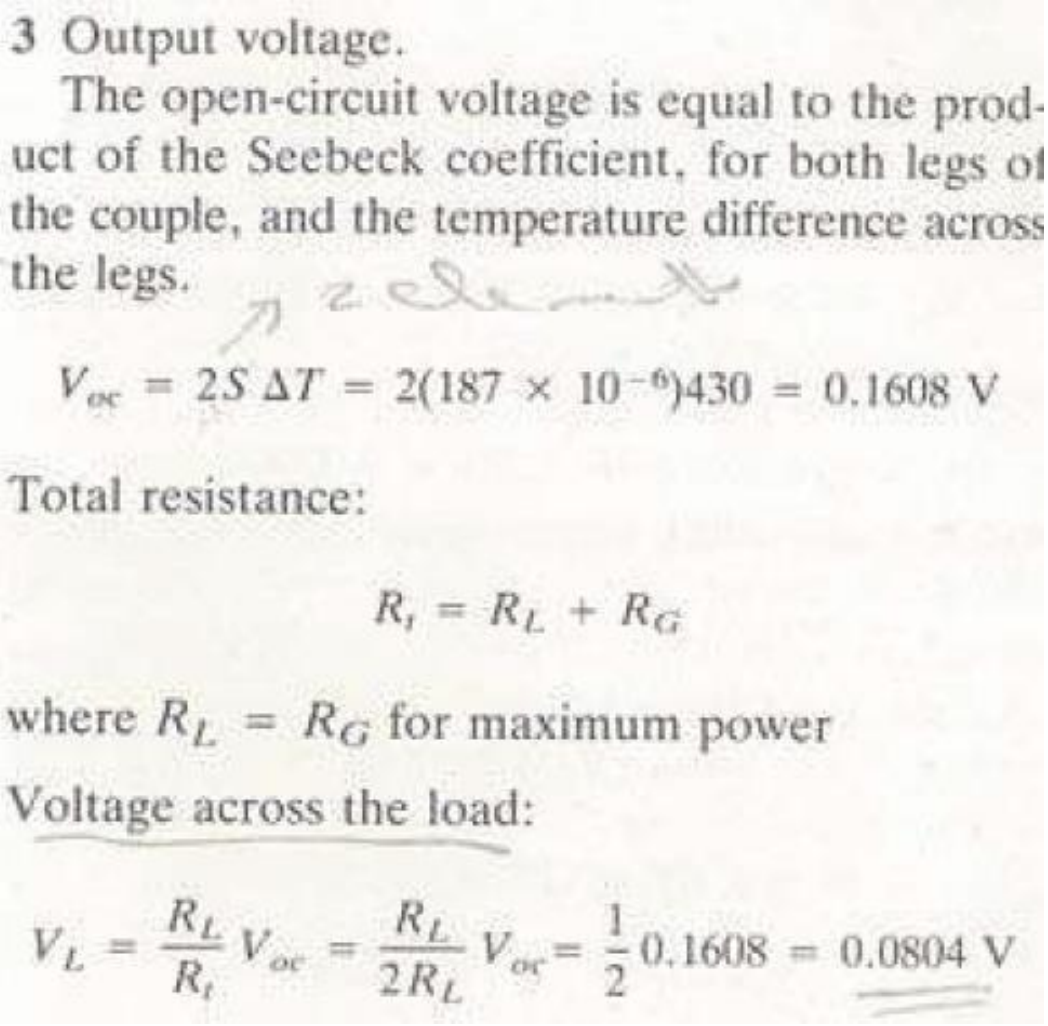
$$= \frac{(187 \times 10^{-6})^2}{(1.64 \times 10^{-3})0.0146}$$

$$= 1.460 \times 10^{-3}\ 1/\mathrm{K}$$

$$\eta_{mp} = \frac{\Delta T}{T_h}\frac{1}{\dfrac{4}{ZT_h} + 2 - \dfrac{1}{2}\dfrac{\Delta T}{T_h}}$$

$$= \frac{430}{725}\frac{1}{\dfrac{4}{(1.460 \times 10^{-3})725} + 2 - \dfrac{1}{2}\dfrac{430}{725}}$$

$$= 0.1082$$



3 Output voltage.

The open-circuit voltage is equal to the product of the Seebeck coefficient, for both legs of the couple, and the temperature difference across the legs. 2 [illegible]

$$V_{oc} = 2S\,\Delta T = 2(187 \times 10^{-6})430 = 0.1608 \text{ V}$$

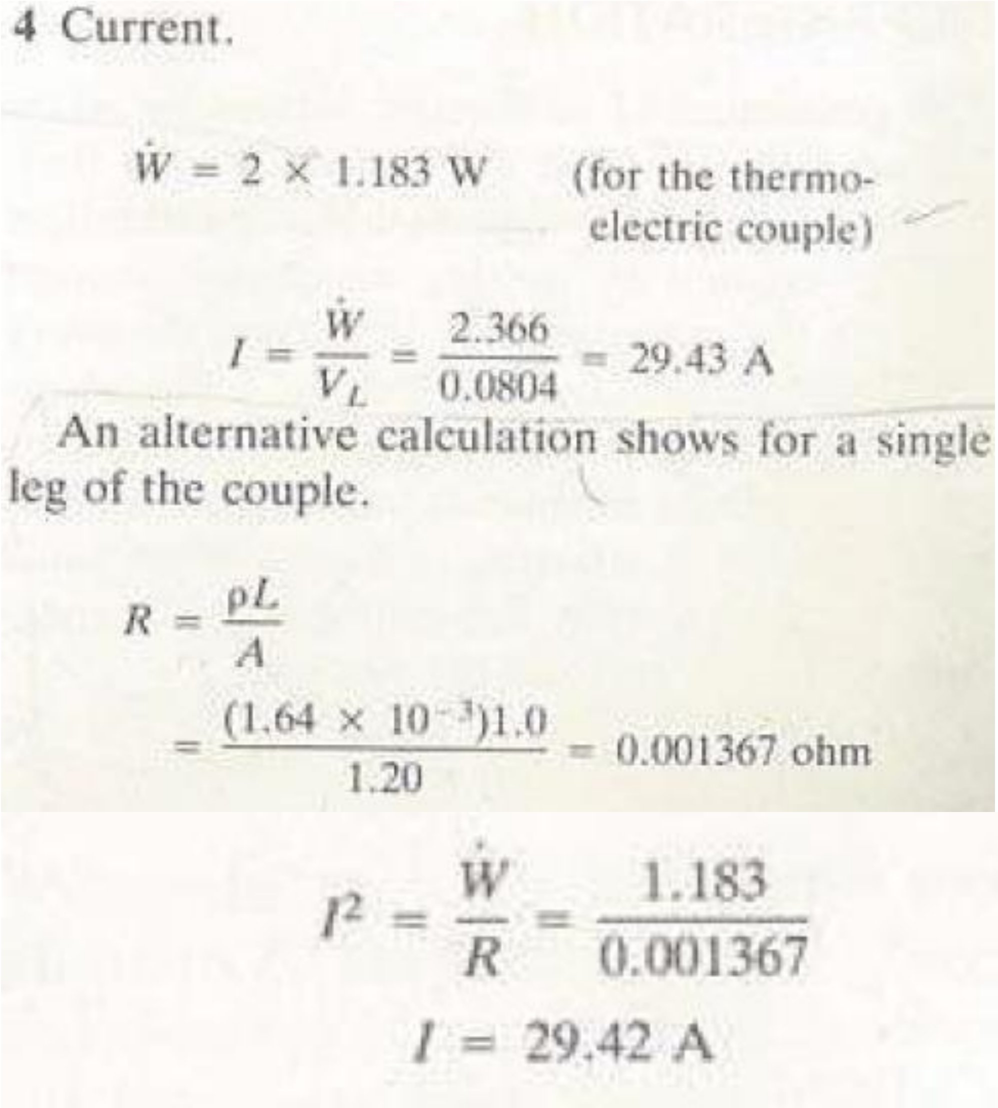
Total resistance:

$$R_t = R_L + R_G$$

where $R_L = R_G$ for maximum power

Voltage across the load:

$$V_L = \frac{R_L}{R_t} V_{oc} = \frac{R_L}{2R_L} V_{oc} = \frac{1}{2} 0.1608 = 0.0804 \text{ V}$$



4 Current.

$$\dot{W} = 2 \times 1.183 \text{ W} \qquad \text{(for the thermoelectric couple)}$$

$$I = \frac{\dot{W}}{V_L} = \frac{2.366}{0.0804} = 29.43 \text{ A}$$

An alternative calculation shows for a single leg of the couple.

$$R = \frac{\rho L}{A}$$

$$= \frac{(1.64 \times 10^{-3})1.0}{1.20} = 0.001367 \text{ ohm}$$

$$I^2 = \frac{\dot{W}}{R} = \frac{1.183}{0.001367}$$

$$I = 29.42 \text{ A}$$

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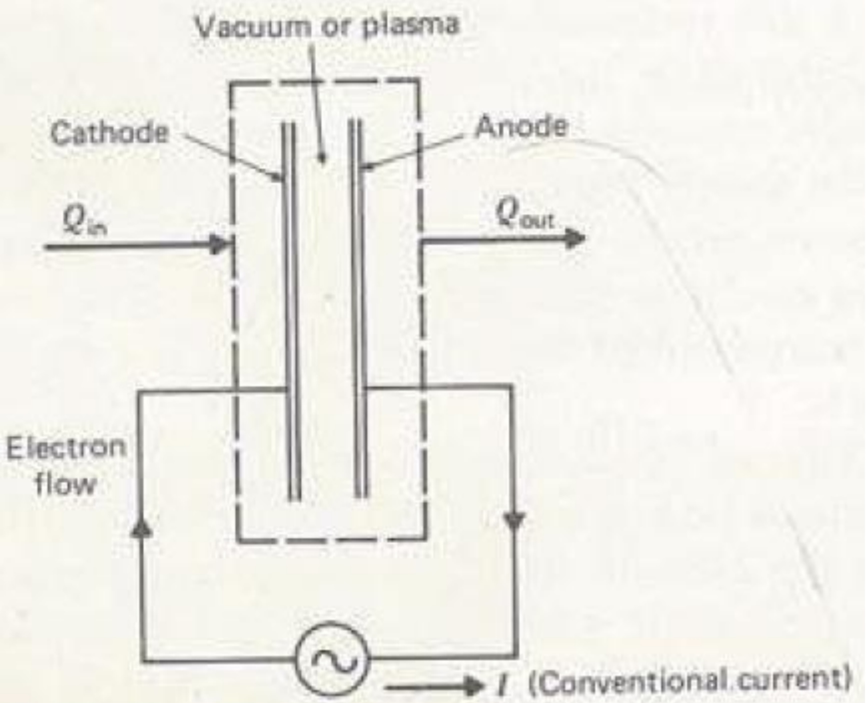
Thermionic Power

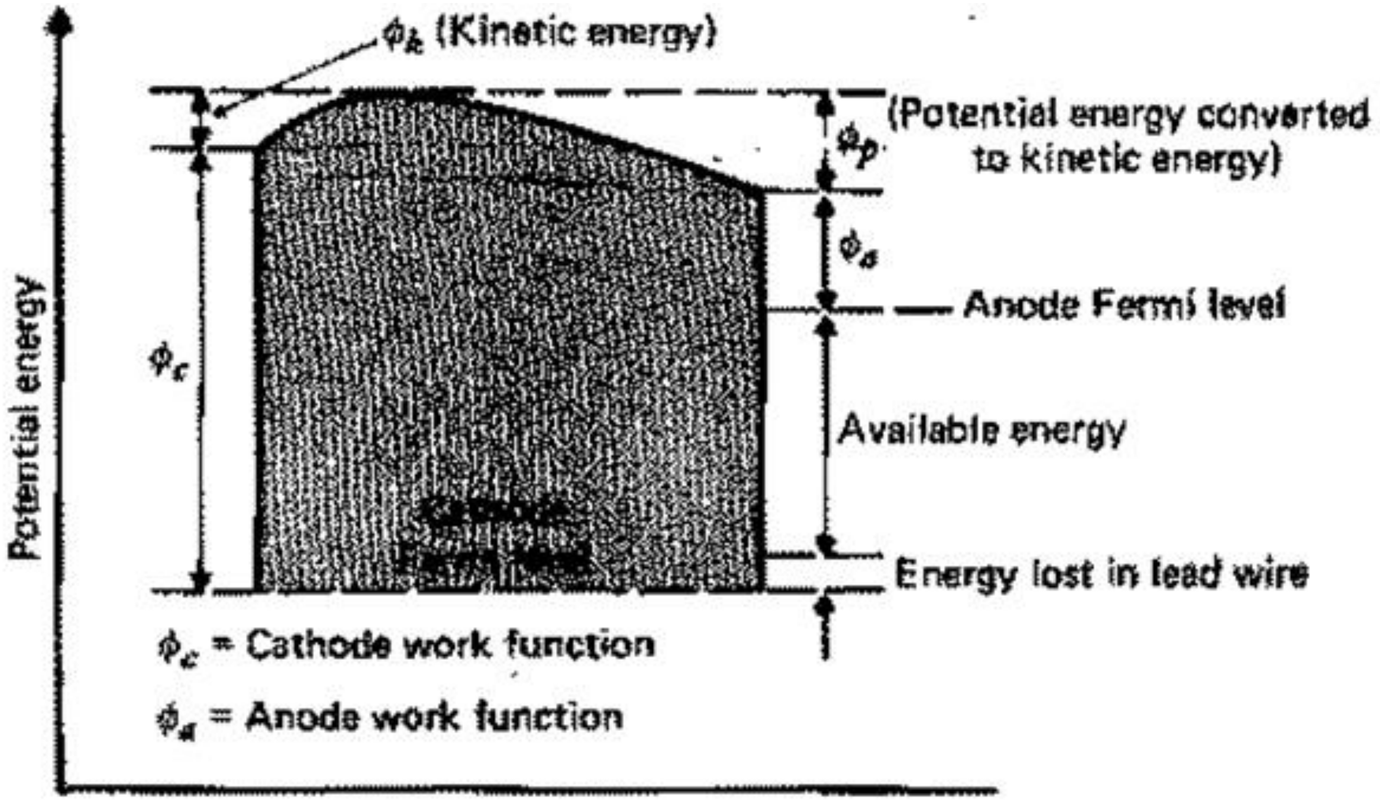
- A simple thermionic converter consists of two parallel plates enclosed in a vacuum.
- Heat is transferred to the cathode where the electrons boil off by the high temperature and flow to the anode at a lower temperature.
- When the two electrodes are connected externally, electrons flow from the anode back to the cathode.



Fermi-level

- Free electrons in the outermost orbits are not strongly bound to the nucleus, those electrons can move from one nucleus to another. Free electrons have certain energy levels; the highest energy level is the Fermi-level for free electrons.
- Free electrons in a cathode have a lower Fermi level than that in the anode – they possess more energy in anode.
- Energy that is required to escape from the cathode is called cathode work function, similarly the anode work function is the energy required for the free electrons to escape from the anode

Energy levels



Thermionic energy converter electron potential.

Work functions

- When the cathode is heated, free electrons acquiring energy more than Φc will escape from cathode.
- When those electrons strike and enter the anode, they loose their kinetic energy Φk and Φa. The lost energy is released as heat from the low temperature anode.
- Space charge is formed in the inter-electrode gap as a result of electrons repulsing each other, this adds another energy barrier Φp to be overcomed by the electrons.
- This space charge can be minimized using very small gap (0.1 mm) close-spaced diodes, or by introducing a readily ionized gas

Thermionic converter materials

- Characteristics of Cathode material:
  1. Low thermal emissivity to reduce radiation losses
  2. Low thermal and electrical resistivity
  3. Ease of fabrication
  4. Low Fermi-level and high Φc
- Examples: Tungsten, uranium carbide, barium oxide

Anode material

- Characteristics of anode material:

  1. Low thermal emissivity to reduce radiation losses
  2. Low thermal and electrical resistivity
  3. Chemically stable
  4. High Fermi-level and low Φa

Performance of thermionic converter

- The saturation current density, which is the maximum current, is given by Richardson Dushmen equation.

  $J_{max} = AT_c^2 \exp(- \varphi_c / kTc)$ amp/cm^2

  Where k: Boltzman constant = 1.38054×10^{-23} J/K

  A= 120 amp/K^{2}cm^2

- Or

  $J_{max} = A\, T_c^2 \exp(- 11605\, Vc / Tc)$ amp/cm^2

- Note $Vc = \varphi_c/e = \varphi_c / 1.60210\times10^{-19}$

Power & efficiency

- W per unit area

  $W = J_{max}(Vc - Va)$
- Thermal efficiency:

  η_{th}= output power /input heat = W/Qs
- $\eta_{th} = (\varphi_c - \varphi_a - \varphi_L) / (\varphi_c + 2kTc + Q_{r+L})$

  where QL: lost in wires.

  2kTc: K.E

  Q_{r+L}= radiation and conduction losses from cathode
- Now if QL = 0 and neglecting conduction losses.
- $\eta_{th} = (\varphi_c - \varphi_a - \varphi_L) / (\varphi_c + 2kTc + Qr)=$

  $= J_{max} (Vc - Va) / [J_{max} (Vc+2kTc/e) + Qr]$

  and $Qr = \sigma Ac(Tc^4 - Ta^4) / (1/\varepsilon_c + 1/\varepsilon_a - 1)$

$\sigma = 5.6697\text{x}10^{-12}$, ε_c & ε_a : emissivity of cathode and anode respectively.

Types of thermionic converters

- Vacuum diode converter: where the anode-cathode clearance is less than 0. 1 mm. The disadvantage of this type is that the mutual repulsion of electrons inhibits the electron flow from the emitter.
- For example; the tungsten impregnated cathode has current density of 1.9A/cm^2 at 1510 cathode temperature, the maximum power is 0.82 W/cm^2 with an efficiency of 10%.

Types of thermionic converters

- Gas filled diode converter: the disadvantage is an increase in the heat transfer between the diodes by convection. There are two main types:

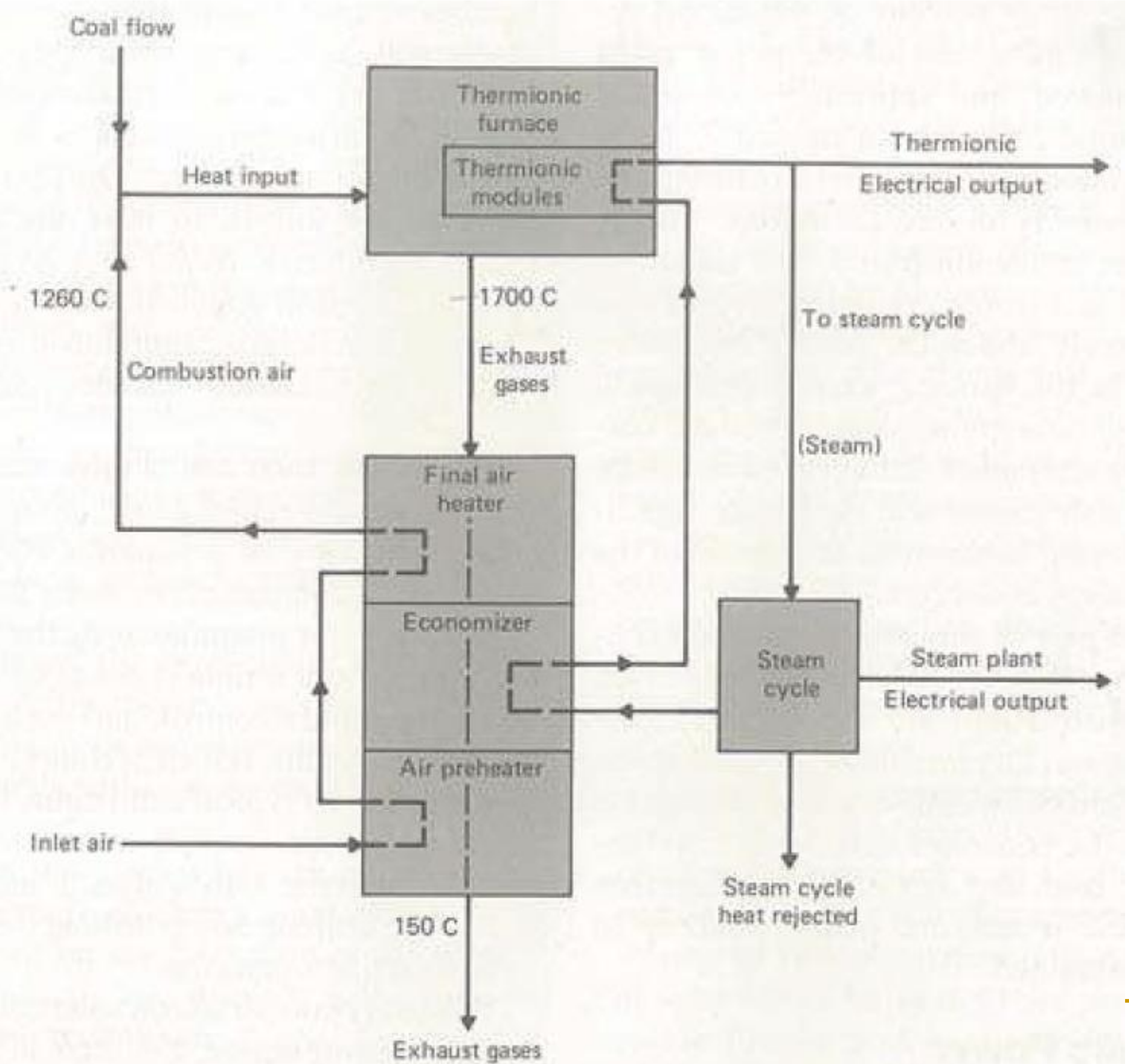
a) High pressure: using cesium vapor where the temperature of cathode reaches 1800 K in order to ionize the gas

b) Low pressure.

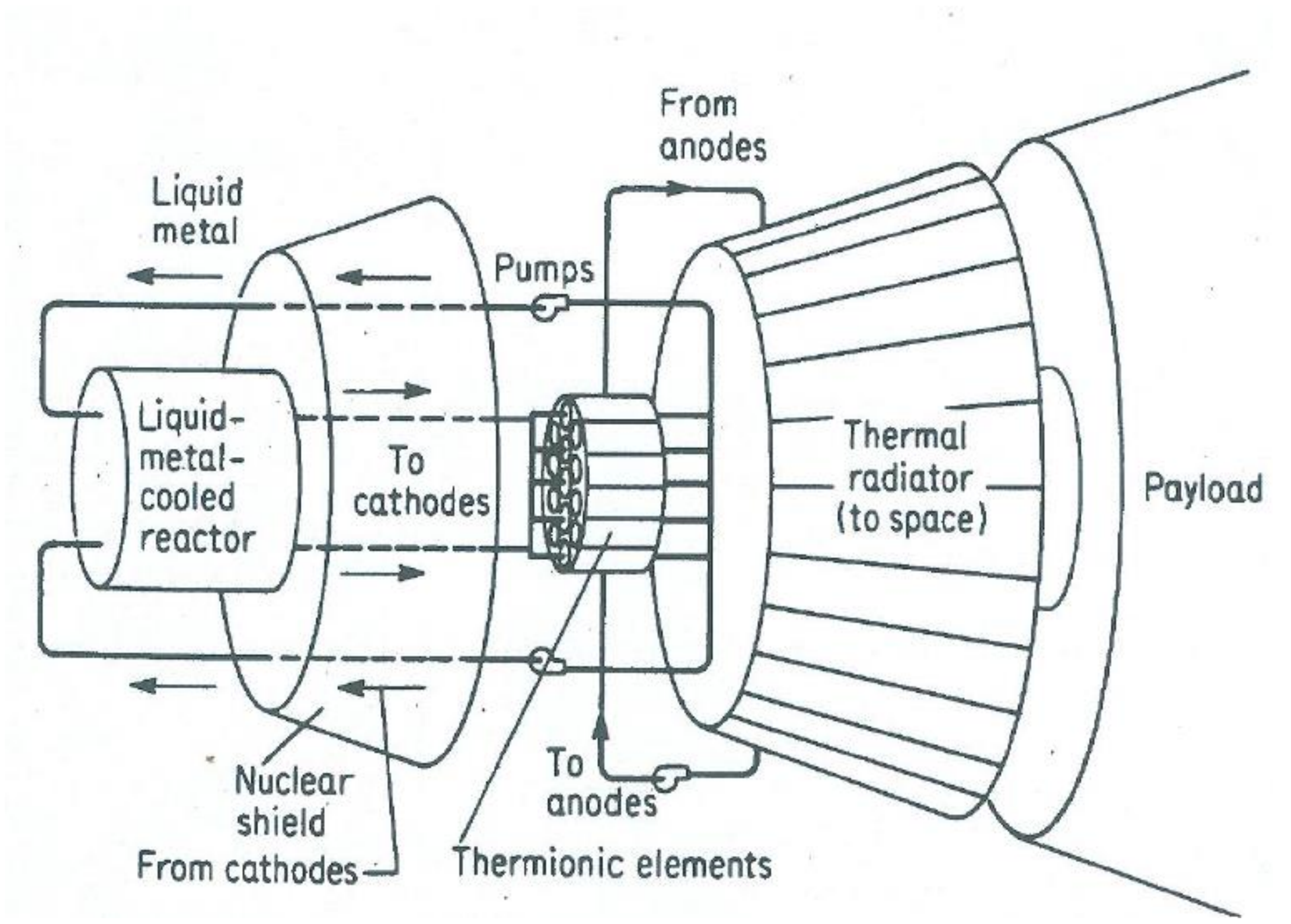
Applications of thermionic converter

- Space power supply: the converter has light weight and insensitivity to radiation damages. No problems with heat rejection from anode. It may use solar or nuclear energy.
- Thermionic converter using nuclear fuel: may use the fuel rod as a cathode such as using uranium carbide. The thermionic converter can be used as a topping device to increase the thermal efficiency

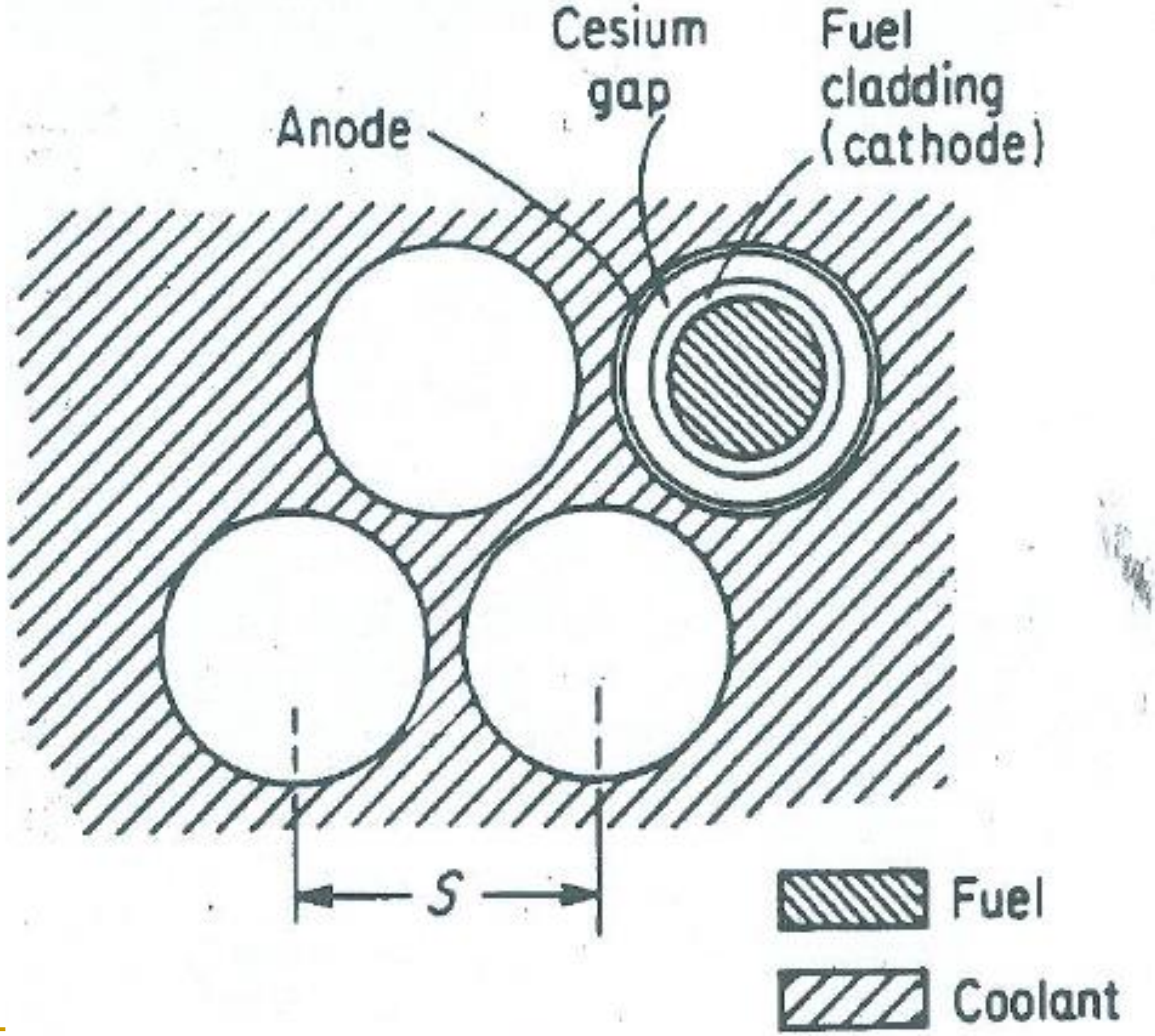
Block diagram for a thermionic topping power system.



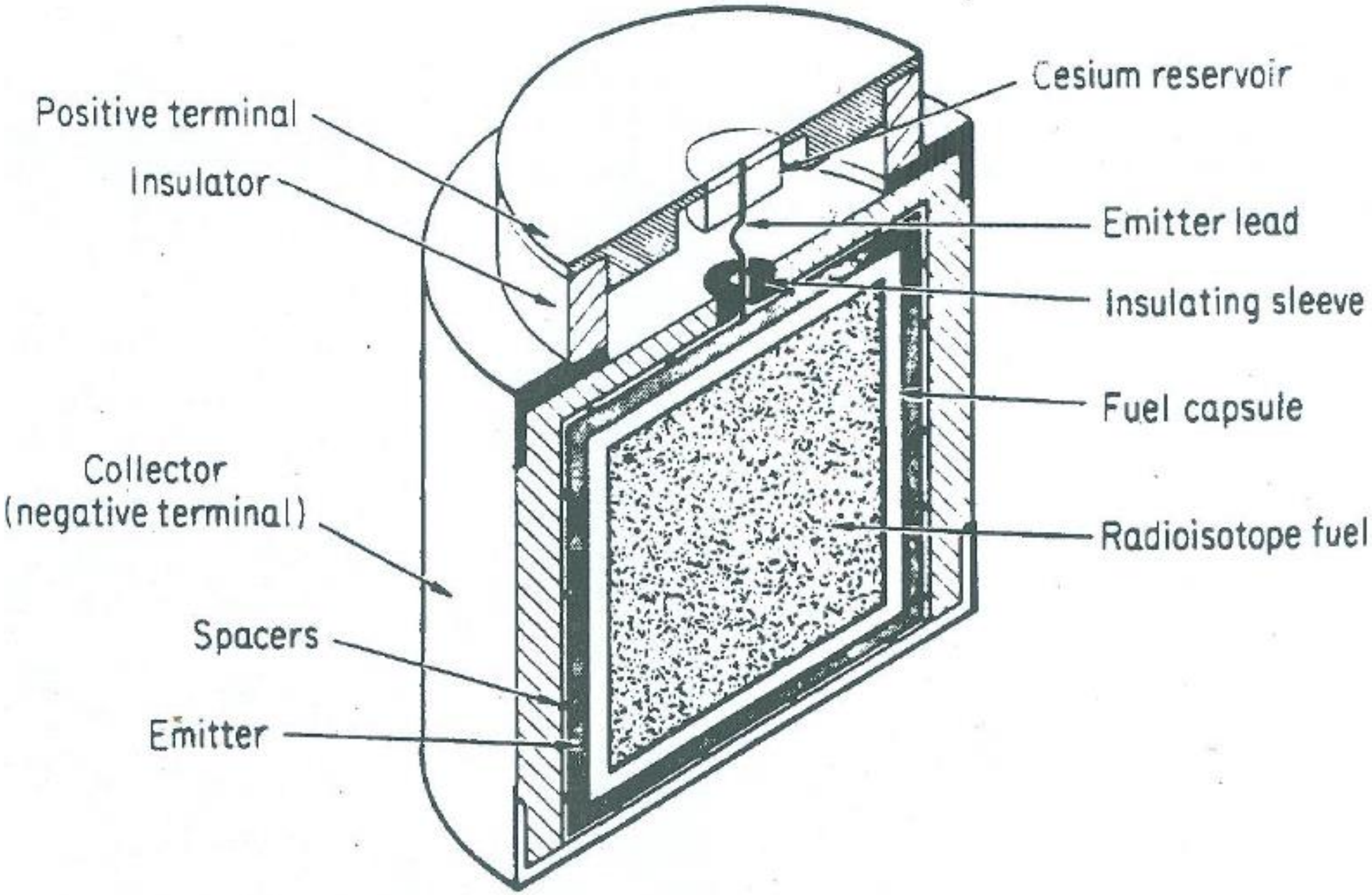
Schematic drawing of an out-of-pile nuclear thermionic power system for space applications.



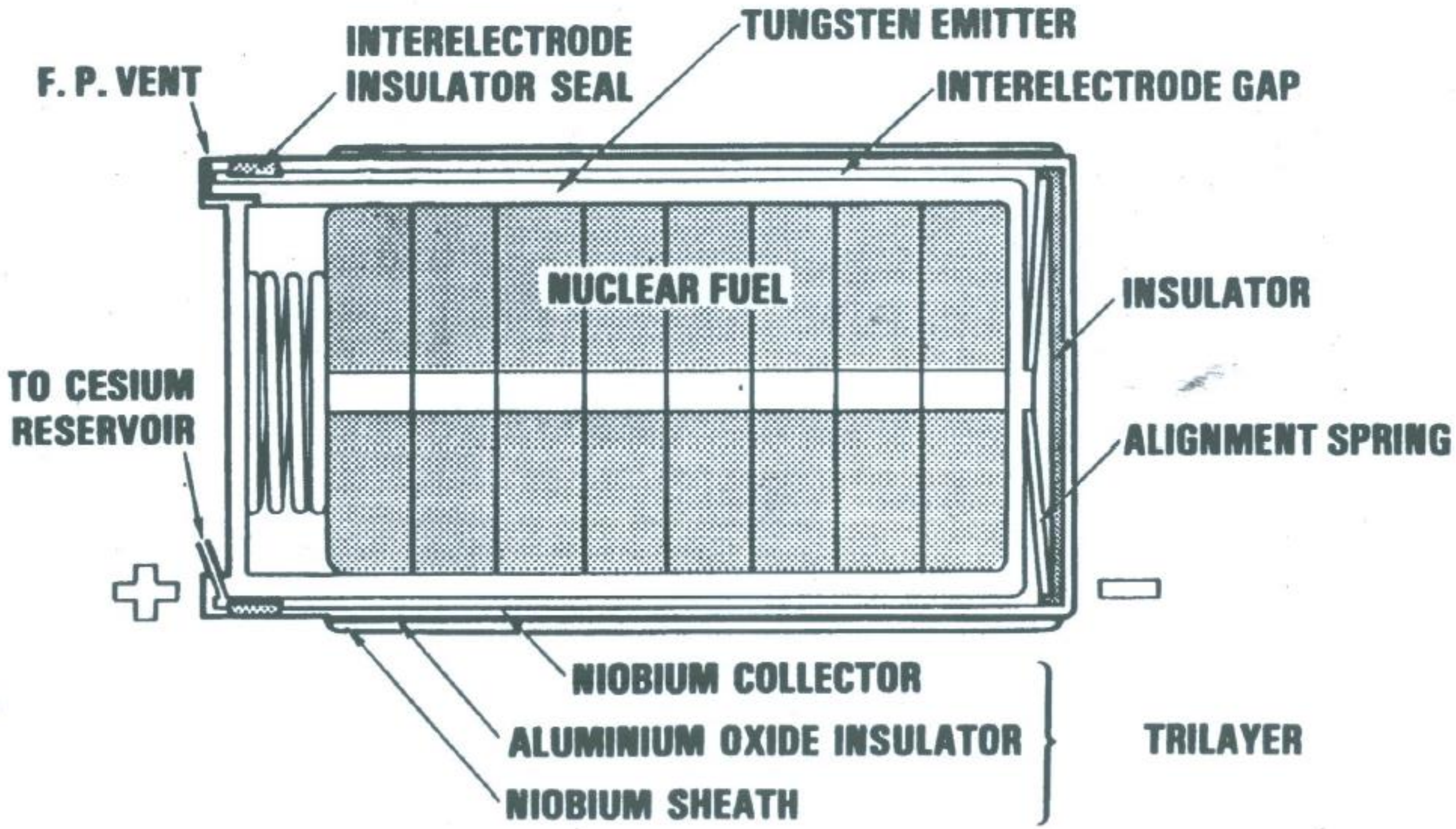
In-pile thermionic cell arrangements: (a) internal fuel



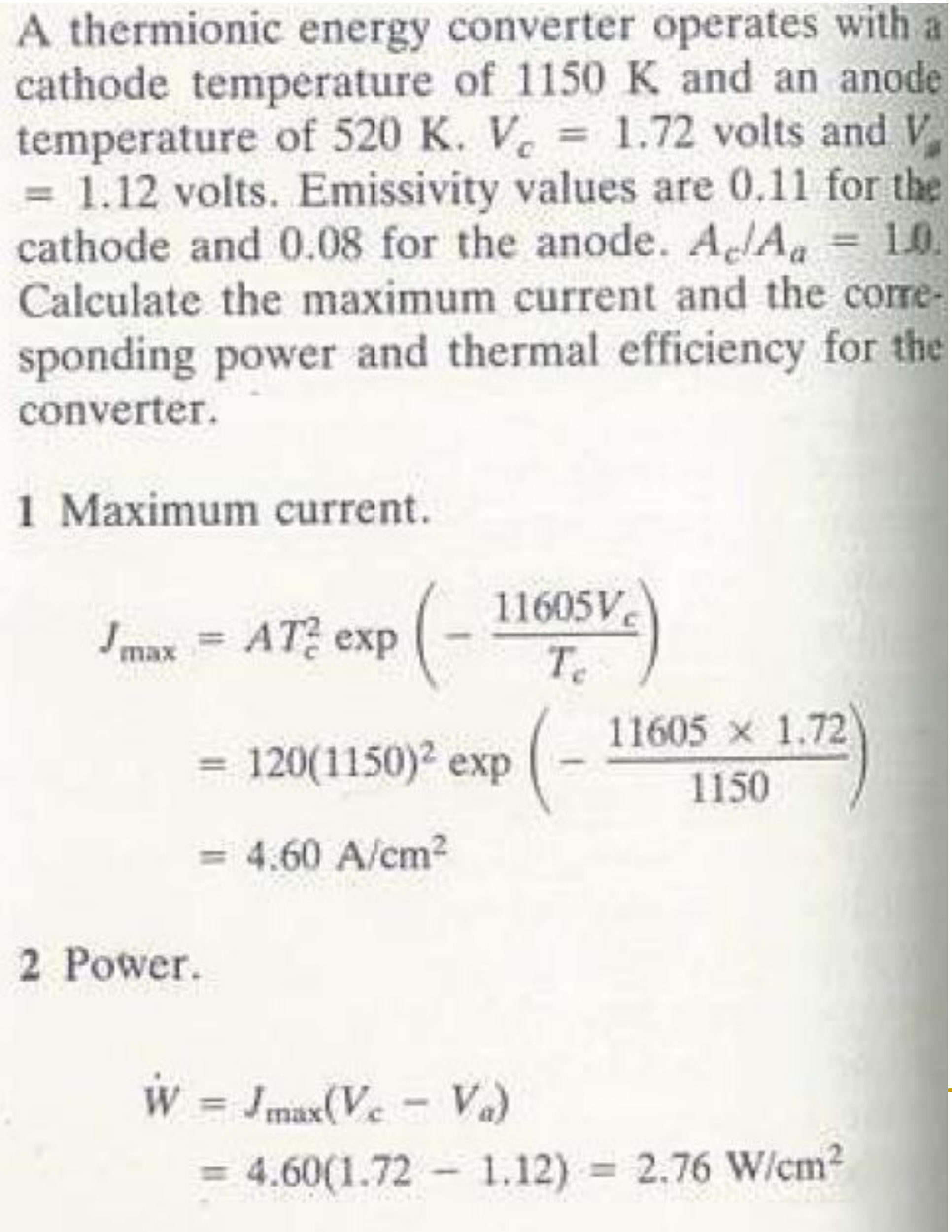
Isomite thermionic power cell.



SCHEMATIC OF IN-CORE THERMIONIC CELL



example 12.6 p.432 Sorenson



A thermionic energy converter operates with a cathode temperature of 1150 K and an anode temperature of 520 K. V_c = 1.72 volts and V_a = 1.12 volts. Emissivity values are 0.11 for the cathode and 0.08 for the anode. A_c/A_a = 1.0. Calculate the maximum current and the corresponding power and thermal efficiency for the converter.

1 Maximum current.

$$J_{\max} = AT_c^2 \exp\left(-\frac{11605V_c}{T_c}\right)$$

$$= 120(1150)^2 \exp\left(-\frac{11605 \times 1.72}{1150}\right)$$

$$= 4.60 \text{ A/cm}^2$$

2 Power.

$$\dot{W} = J_{\max}(V_c - V_a)$$

$$= 4.60(1.72 - 1.12) = 2.76 \text{ W/cm}^2$$

3 Heat supplied.

$$F_e = \frac{1}{\dfrac{1}{e_c} + \dfrac{1}{e_a} - 1}$$

$$= \frac{1}{\dfrac{1}{0.11} + \dfrac{1}{0.08} - 1} = 0.0486$$

$$\dot{Q}_r = \sigma F_e (T_c^4 - T_a^4)$$

$$= (5.6697 \times 10^{-12}) 0.0486 [(1150)^4 - (520)^4]$$

$$= 0.462 \text{ W/cm}^2$$

$$\dot{Q}_s = J_{\max}\left(V_e + 2\frac{k}{e}T_c\right) + \dot{Q}_r = \phi_c + 2kT_c + \dot{Q}_c$$

$$= 4.60[1.72 + 2(0.86171 \times 10^{-4})1150] + 0.46$$

$$= 8.82 + 0.46 = 9.28 \text{ W/cm}^2$$

4 Thermal efficiency.

$$\eta_t = \frac{\dot{W}}{\dot{Q}_s} = \frac{2.76}{9.28} = 0.297$$

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Fuel Cell

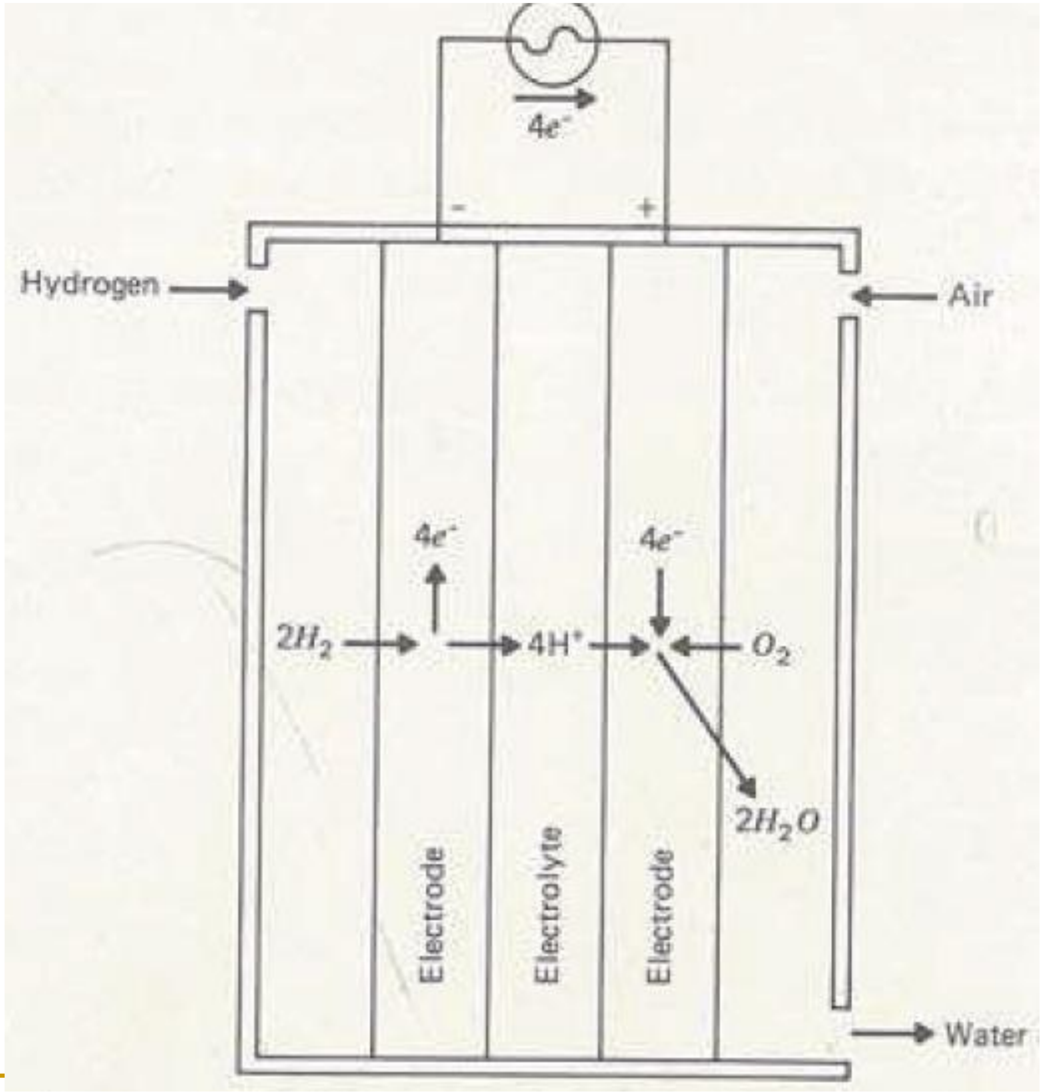
- Fuel cell is a device in which chemical energy is converted directly to electrical energy,
- since the fuel cell doesn't operate in a thermodynamic cycle; its thermal efficiency is not limited by the second law of thermodynamics (its efficiency can exceed Carnot efficiency imposed by this law).
- Fuel cell is similar to a battery by structure and function. Both contain two electrodes and electrolyte or a matrix.
- Fuel cell can operate continuously for a long time as long as fuel is supplied to electrodes.
- Secondary batteries are rechargeable while fuel cells are not rechargeable since the products of reaction are discarded.

Operation principles

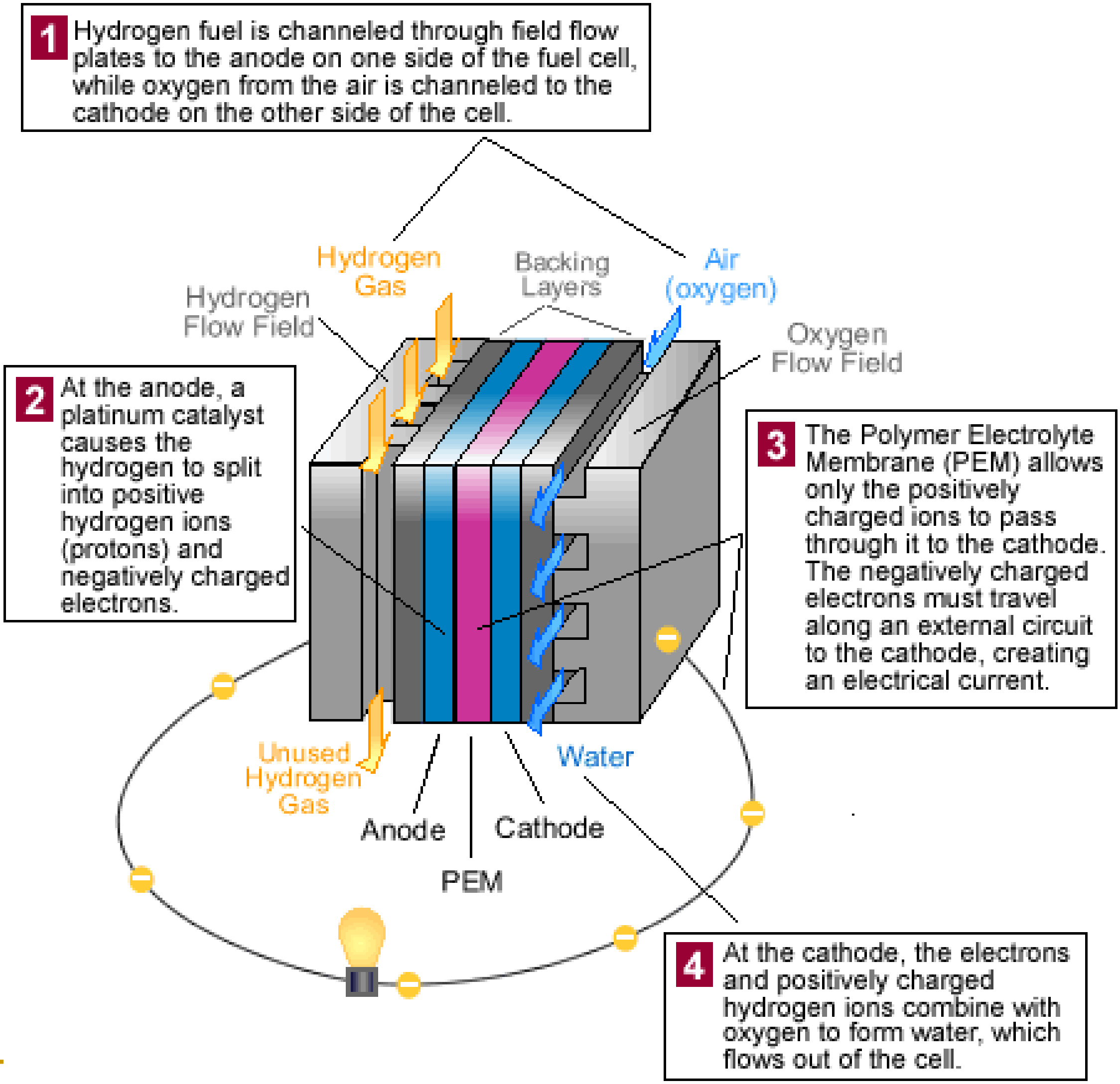
- The basic principle of operation is the creation of two chemical reactions; one reaction releases electrons that travel through an external circuit and return to be absorbed in the second chemical reaction.
- The two reactions occur on two electrodes, which are separated by a liquid or solid electrolyte through which ions will travel.

hydrogen/oxygen cell

- The hydrogen which is the fuel, reacts on the anode surface producing electrons and ions.
- Anode reaction: $2H2 \longrightarrow 4e- + 4H^{+}$
- The produced electrons travel through the external circuit to the cathode, while H+ ions migrate through the electrolyte to the cathode where it combines with electrons and oxygen to form water.
- Cathode reaction: $4H^{+} + 4e- + O2 \longrightarrow 2\ H2O$
- The electrolyte in this case is an acidic medium.



Hydrogen /oxygen fuel cell



1 Hydrogen fuel is channeled through field flow plates to the anode on one side of the fuel cell, while oxygen from the air is channeled to the cathode on the other side of the cell.

2 At the anode, a platinum catalyst causes the hydrogen to split into positive hydrogen ions (protons) and negatively charged electrons.

3 The Polymer Electrolyte Membrane (PEM) allows only the positively charged ions to pass through it to the cathode. The negatively charged electrons must travel along an external circuit to the cathode, creating an electrical current.

4 At the cathode, the electrons and positively charged hydrogen ions combine with oxygen to form water, which flows out of the cell.

http://www.mpoweruk.com/fuel_cells.htm

Methane/air fuel cell

- methane reacts at the anode as:

$$CH4 \quad + \quad 2\ H2O \quad \longrightarrow \quad CO2 \ + \ 8H^{+} \quad + \ 8e\text{-}$$

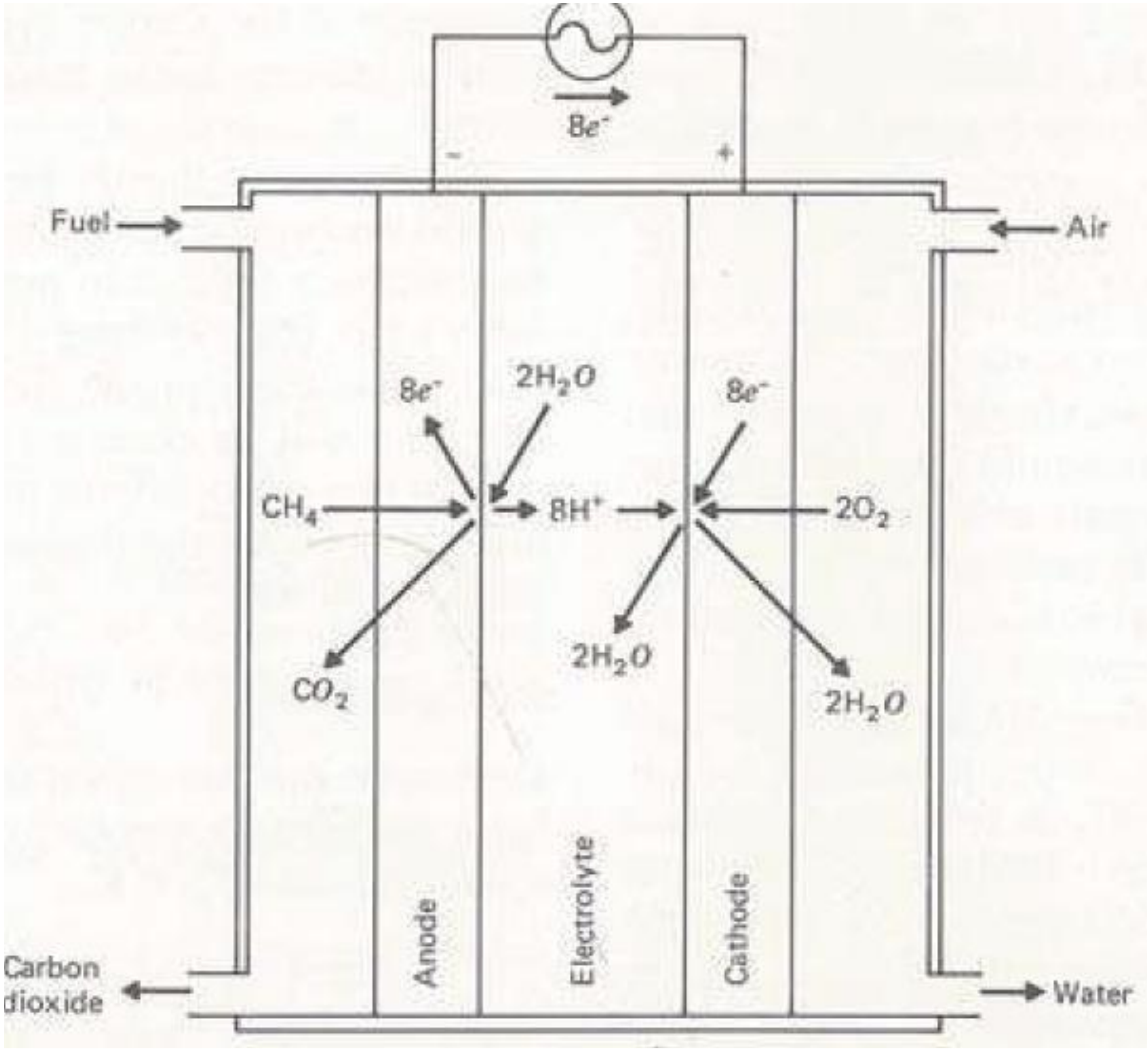
- While CO2 is rejected outside, ions travel through electrolyte to the cathode where the following reaction is produced:

$$O2 \ + \ 8H^{+} \quad + \ 8e\text{-} \quad \longrightarrow 4H2O$$

- Water is a by product of the fuel cell since the net reaction is:

$$CH4 \quad + \quad 2O2 \quad \longrightarrow \quad CO2 \quad + \quad 2H2O$$

Methane/air fuel cell



Fuel cell electrode material

- Fuel cell electrodes must have the following characteristics:

  a) Porosity: proper size of pours so that both fuel and electrolyte can penetrate it for a proper contact.

  b) Catalyst: it should contain a chemical catalyst that breaks the fuel compound into atoms

  c) Electrical conductivity: must be able to conduct the electrons to the terminal.

  d) Resistance to corrosion in the potential range of operation.

- Examples of electrode catalytic surfaces are platinum for anode and palladium for cathode, while nickel can be used as substrate.
- To prepare the electrode, the material is chosen, obtained in the powder form with the required particle size, pressed and sintered to produce porous sheets

Fuel cell electrolyte

- Fuel cell electrolyte: Fuel cell can be classified according to the used electrolytes; three types are known:
  1. Aqueous electrolytes
  2. Molten salt electrolytes
  3. Solid electrolytes

Aqueous electrolytes

- It operates in temperature range of 0-200ºC; it can be either acidic or basic.

a) Alkaline electrolytes (e.g. OH):

Cathode reaction $O2 + 2H2O + 4e- \longrightarrow 4OH^-$

Anode reaction $2H2 + 4OH^- \longrightarrow 4H2O + 4e-$

Overall reaction $O2 + 2H2 \longrightarrow 2H2O$

b) Acid electrolyte:

Anode reaction $2H2 \longrightarrow 4e- + 4H^+$

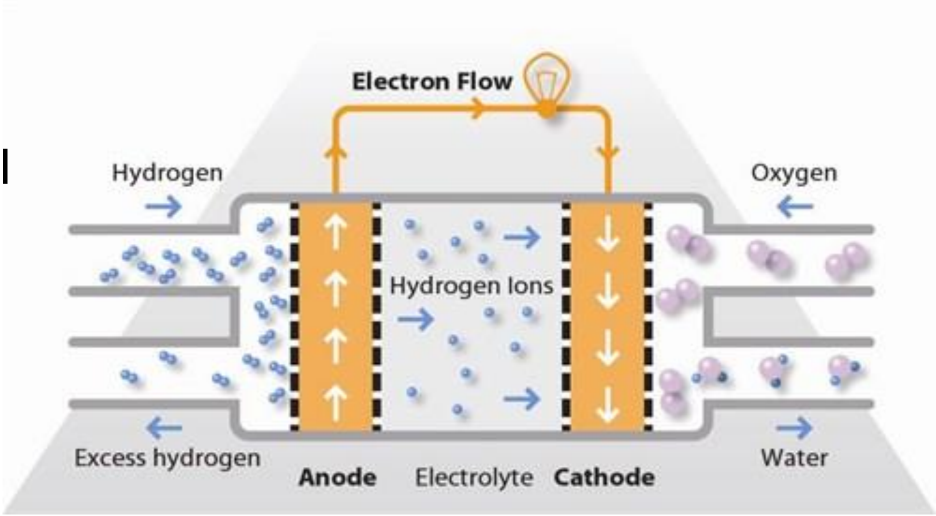
Cathode reaction $4H^+ + 4e- + O2 \longrightarrow 2H2O$

Overall reaction $O2 + 2H2 \longrightarrow 2H2O$

Proton exchange membrane fuel cell PEMFC

(PEMFC) uses a water-based, acidic polymer membrane as its electrolyte, with platinum-based electrodes. PEMFC cells operate at relatively low temperatures (below 100 degrees Celsius). Due to the relatively low temperatures and the use of precious metal-based electrodes, these cells must operate on pure hydrogen.

- The protons pass through the membrane to the cathode side of the cell while the electrons travel in an external circuit, generating the electrical output of the cell.
- On the cathode side, another precious metal electrode combines the protons and electrons with oxygen to produce water, which is expelled as the only waste product;
- oxygen can be provided in a purified form, or extracted at the electrode directly from the air

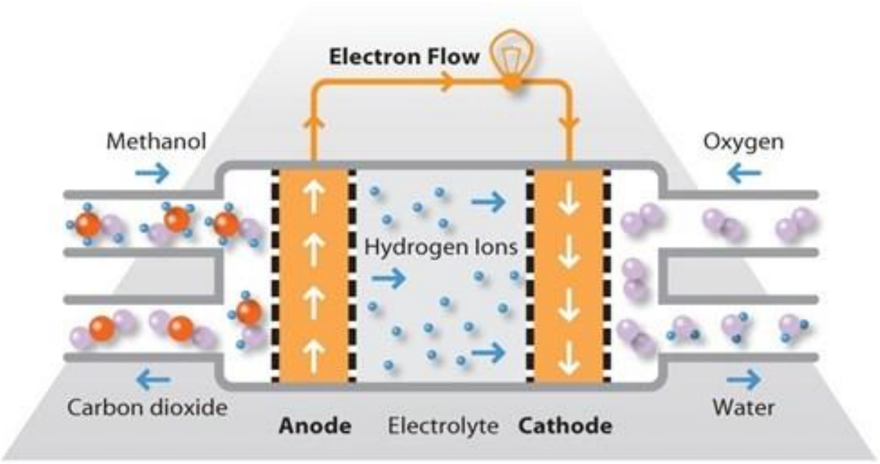


http://www.fuelcelltoday.com/technologies/mcfc

Direct methanol fuel cell (DMFC)

It uses a polymer membrane as an electrolyte. However, the platinum-ruthenium catalyst on the DMFC anode is able to draw the hydrogen from liquid methanol, eliminating the need for a fuel reformer. Therefore pure methanol can be used as fuel, hence the name.

- DMFCs operate in the temperature range from 60ºC to 130ºC .
- used in applications with modest power requirements, such as mobile electronic devices or chargers and portable power packs.
- A number of these units have been sold to commercial warehouses, where the forklift trucks had been conventionally powered with battery packs

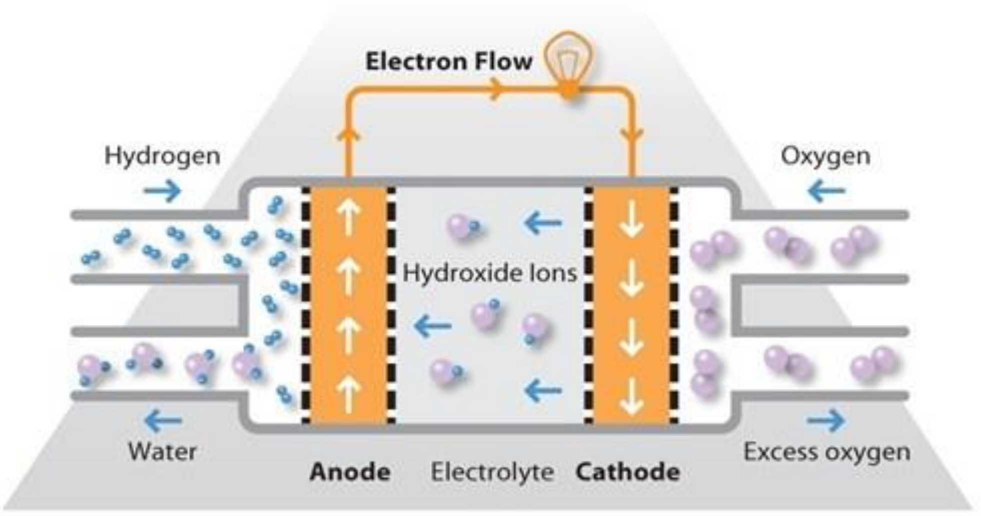


http://www.fuelcelltoday.com/technologies/mcfc

Alkaline fuel cells (AFCs)

Originally used by NASA in the space program to produce both electricity and water aboard spacecraft. AFCs continued to be used on NASA space shuttles throughout the program, alongside a limited number of commercial applications.

- AFCs use an alkaline electrolyte such as potassium hydroxide in water and are generally fueled with pure hydrogen.
- Typical operating temperatures are now around 70ºC.
- As a result of the low operating temperature, it is not necessary to employ a platinum catalyst in the system



http://www.fuelcelltoday.com/technologies/mcfc

Molten salt electrolytes

- operate in temperature range of 500-700ºC (e.g. molten carbonates):

Anode reaction H2 + $CO_3^{-2} \longrightarrow H_2O + CO_2 + 2e^-$

Cathode reaction ½ $O_2 + CO_2 + 2e^- \longrightarrow CO_3^{-2}$

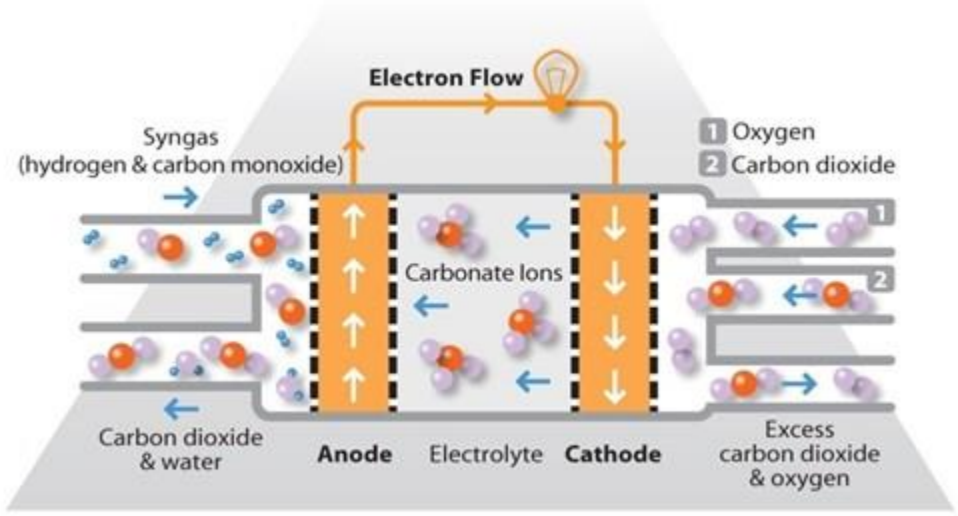
……………………………………………………………

Overall reaction $H_2 + \frac{1}{2} O_2 \longrightarrow H_2O$

Molten carbonate fuel cells (MCFCs

Use a molten carbonate salt suspended in a porous ceramic matrix as the electrolyte. Salts commonly used include lithium carbonate, potassium carbonate and sodium carbonate

- They operate at high temperature, around 650ºC and
- there are several advantages associated with this.
- the high operating temperature dramatically improves reaction kinetics and thus it is not necessary to boost these with a noble metal catalyst.



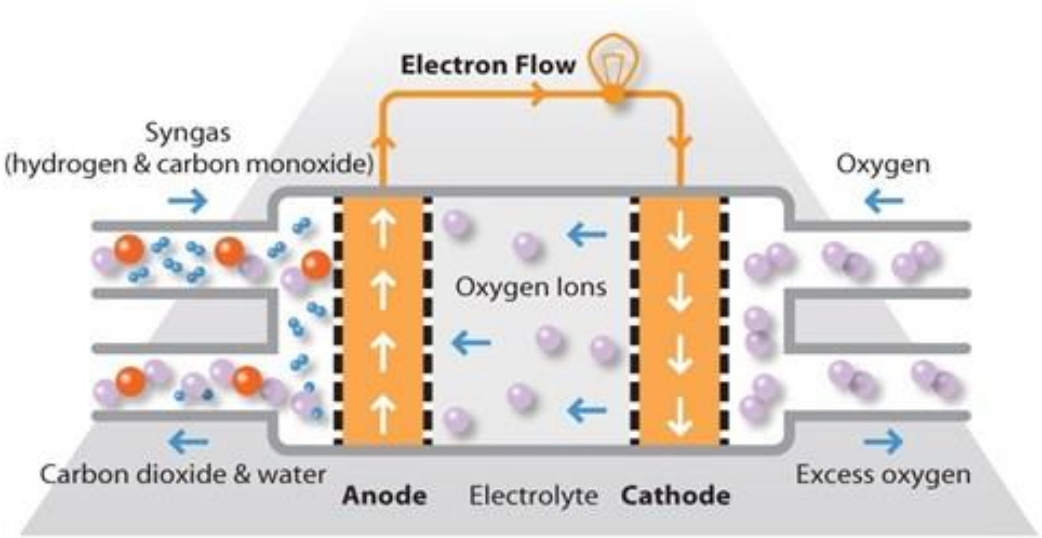
http://www.fuelcelltoday.com/technologies/mcfc

Solid electrolytes

- Operate in temperatures above 700ºC.
- The electrolyte is a solid containing an ion species, which becomes mobile at high temperature. e.g. 85% ZrO_2 metal with 15% CaO
- Anode reaction $H_2 + O^{-2} \longrightarrow H_2O + 2e^-$
- Cathode reaction $\frac{1}{2} O_2 + 2e^- \longrightarrow O^{-2}$
- Overall reaction $H_2 + \frac{1}{2} O_2 \longrightarrow H_2O$

Solid oxide fuel cells

- Solid oxide fuel cells work at very high temperatures, the highest of all the fuel cell types at around 800ºC to 1,000°C.
- They can have efficiencies of over 60% when converting fuel to electricity.
- SOFCs use a solid ceramic electrolyte, such as zirconium oxide stabilized with yttrium oxide, instead of a liquid or membrane.



http://www.fuelcelltoday.com/technologies/mcfc

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Fuel Cell Performance

- Theoretical performance: consider the fuel cell as a control volume operating at steady state steady flow. Then the maximum work that can be obtained is equal to the reversible work, Wrev, which is given as
- $Wrev = \Delta H - T\Delta S$
- $\Delta H = Hp - HR = \sum_{p} nehe - \sum_{R} nihi$
- $\Delta S = Sp - SR = \sum_{P} nese - \sum_{R} nisi$

  Where $h = h_{f}{}^{o} + \Delta h_{298\rightarrow \mathrm{T}}$
- See table A.5 for $h_{f}{}^{o}$, Δh and s
- But g = h –Ts Gibbs free energy
- For isothermal process $\Delta G = \Delta H - T\Delta S = Wrev$

Theoretical Performance

- Theoretical conversion, ε

  $\varepsilon = \Delta G / \Delta H = 1 - T\Delta S / \Delta H$
- ΔH represents heating value of fuel, this implies that as temperature goes up the efficiency goes down, opposite to the Carnot thermodynamic cycle. See table 12.2

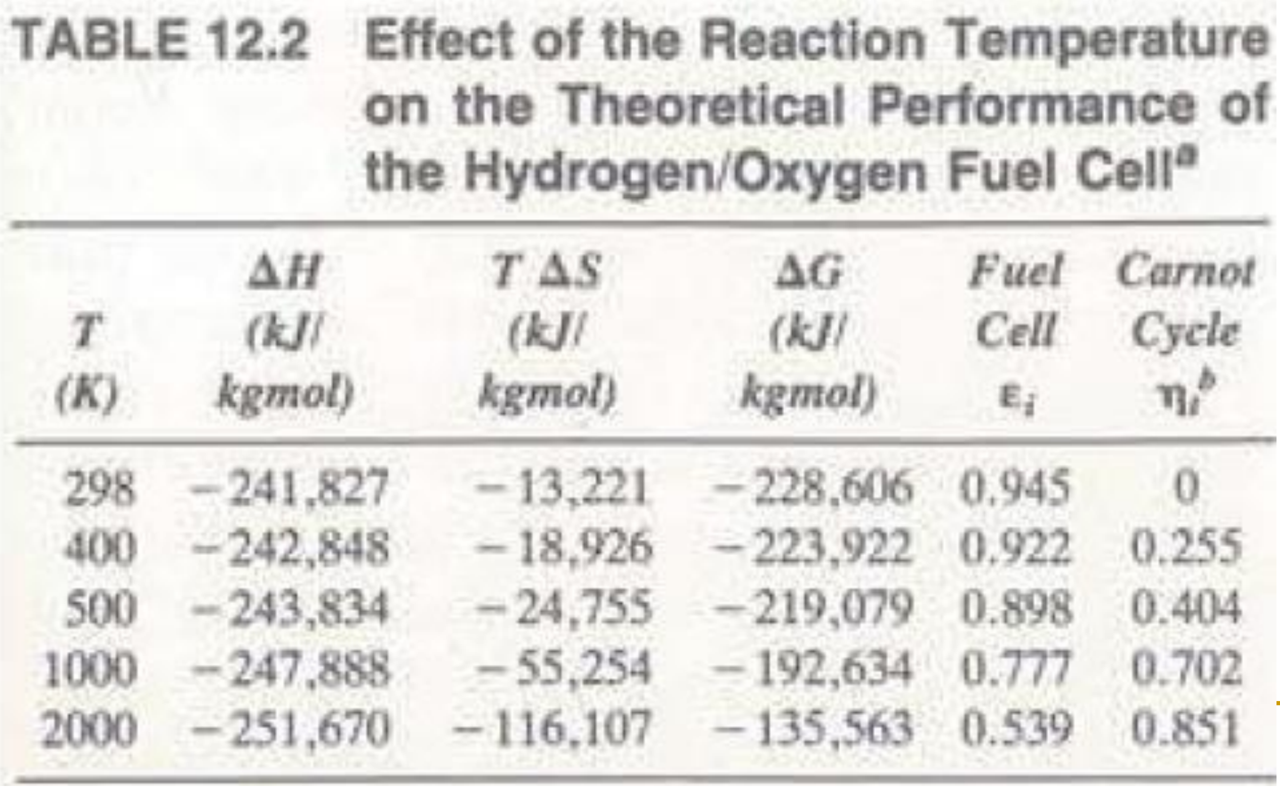
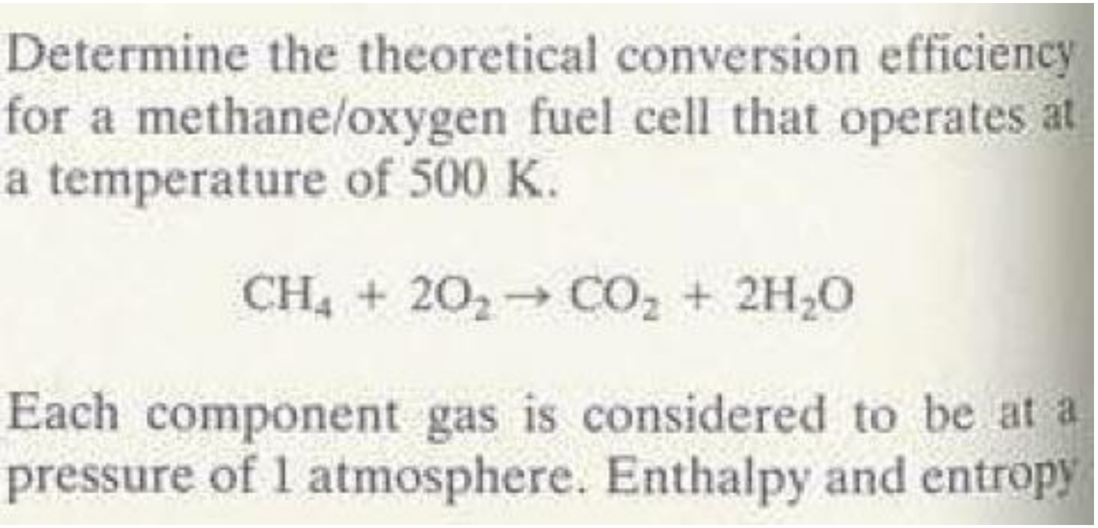


TABLE 12.2 Effect of the Reaction Temperature on the Theoretical Performance of the Hydrogen/Oxygen Fuel Cell[a]

T (K)	ΔH (kJ/kgmol)	$T\Delta S$ (kJ/kgmol)	ΔG (kJ/kgmol)	Fuel Cell ε_i	Carnot Cycle η_i[b]
298	−241,827	−13,221	−228,606	0.945	0
400	−242,848	−18,926	−223,922	0.922	0.255
500	−243,834	−24,755	−219,079	0.898	0.404
1000	−247,888	−55,254	−192,634	0.777	0.702
2000	−251,670	−116,107	−135,563	0.539	0.851

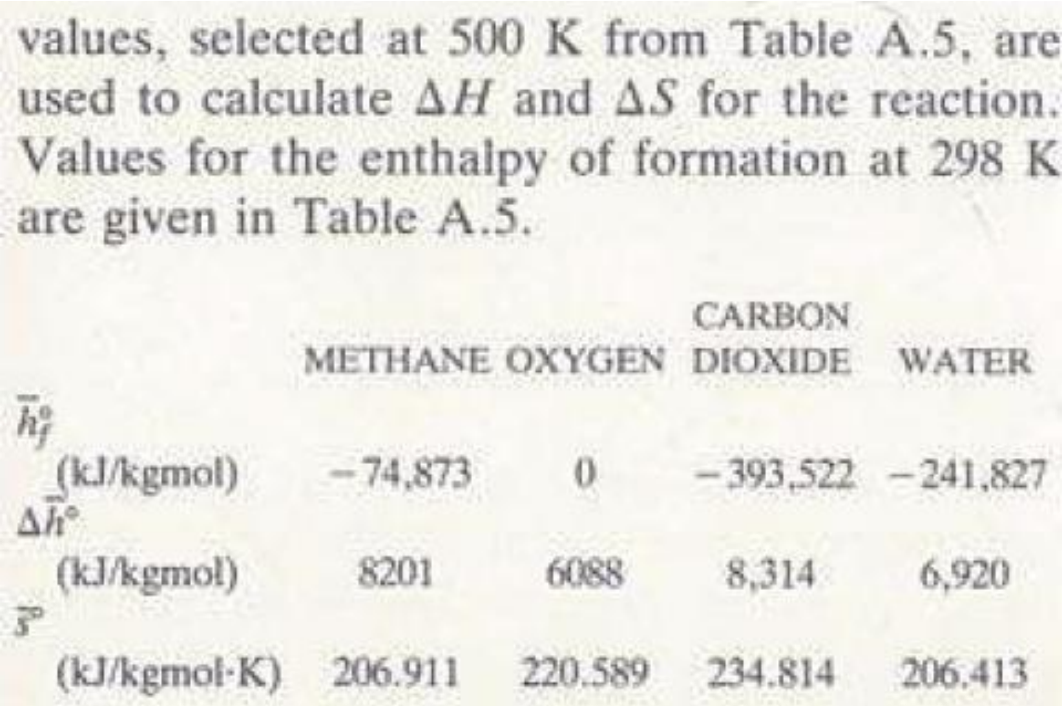
Example 12-10 p446 Sorensen



Determine the theoretical conversion efficiency for a methane/oxygen fuel cell that operates at a temperature of 500 K.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

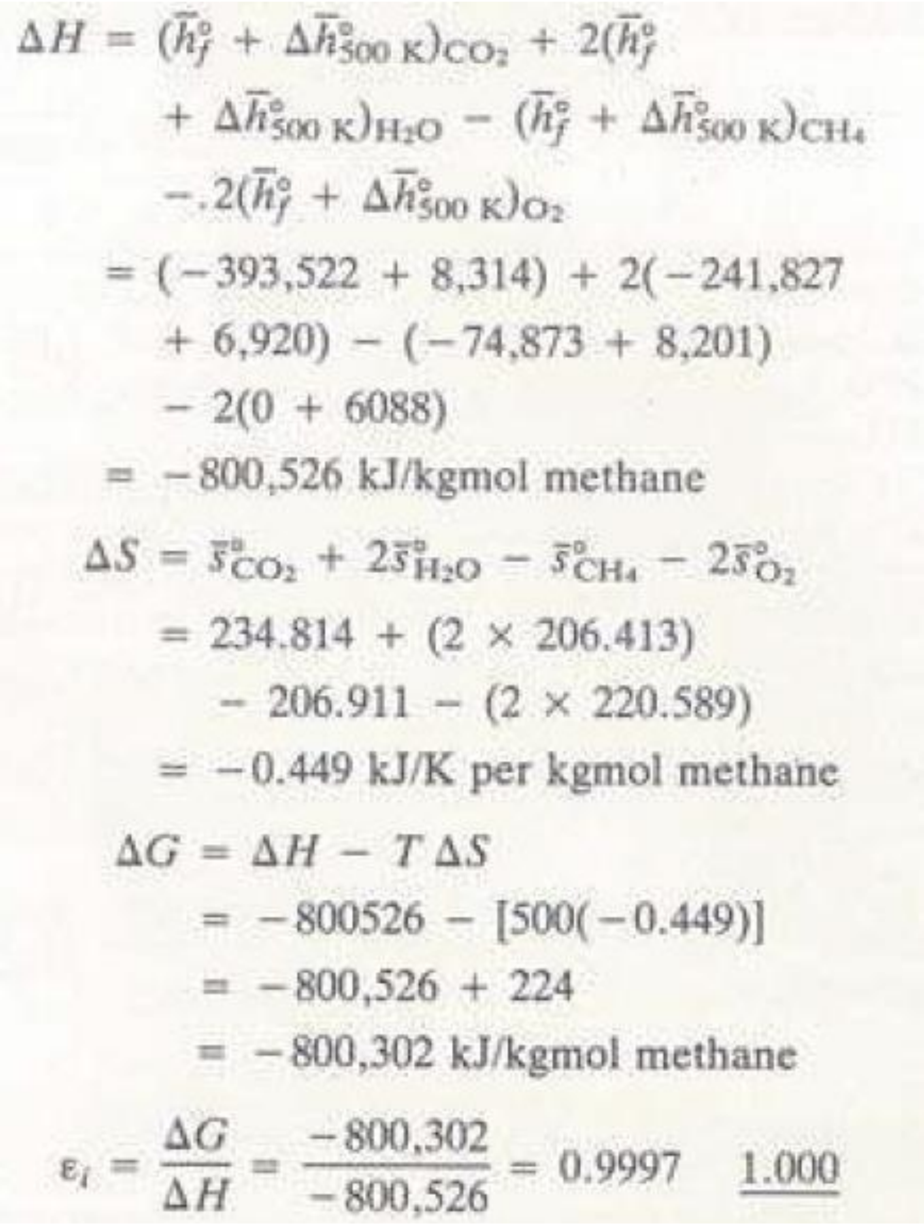
Each component gas is considered to be at a pressure of 1 atmosphere. Enthalpy and entropy



values, selected at 500 K from Table A.5, are used to calculate ΔH and ΔS for the reaction. Values for the enthalpy of formation at 298 K are given in Table A.5.

	METHANE	OXYGEN	CARBON DIOXIDE	WATER
$\bar{h}_f^\circ$ (kJ/kgmol)	−74,873	0	−393,522	−241,827
$\Delta\bar{h}^\circ$ (kJ/kgmol)	8201	6088	8,314	6,920
$\bar{s}^\circ$ (kJ/kgmol·K)	206.911	220.589	234.814	206.413

Example 12-10



$$\begin{aligned}
\Delta H &= (\bar{h}_f^\circ + \Delta\bar{h}^\circ_{500\,\mathrm{K}})_{\mathrm{CO_2}} + 2(\bar{h}_f^\circ \\
&\quad + \Delta\bar{h}^\circ_{500\,\mathrm{K}})_{\mathrm{H_2O}} - (\bar{h}_f^\circ + \Delta\bar{h}^\circ_{500\,\mathrm{K}})_{\mathrm{CH_4}} \\
&\quad - 2(\bar{h}_f^\circ + \Delta\bar{h}^\circ_{500\,\mathrm{K}})_{\mathrm{O_2}} \\
&= (-393{,}522 + 8{,}314) + 2(-241{,}827 \\
&\quad + 6{,}920) - (-74{,}873 + 8{,}201) \\
&\quad - 2(0 + 6088) \\
&= -800{,}526 \text{ kJ/kgmol methane}
\end{aligned}$$

$$\begin{aligned}
\Delta S &= \bar{s}^\circ_{\mathrm{CO_2}} + 2\bar{s}^\circ_{\mathrm{H_2O}} - \bar{s}^\circ_{\mathrm{CH_4}} - 2\bar{s}^\circ_{\mathrm{O_2}} \\
&= 234.814 + (2 \times 206.413) \\
&\quad - 206.911 - (2 \times 220.589) \\
&= -0.449 \text{ kJ/K per kgmol methane}
\end{aligned}$$

$$\begin{aligned}
\Delta G &= \Delta H - T\,\Delta S \\
&= -800526 - [500(-0.449)] \\
&= -800{,}526 + 224 \\
&= -800{,}302 \text{ kJ/kgmol methane}
\end{aligned}$$

$$\varepsilon_i = \frac{\Delta G}{\Delta H} = \frac{-800{,}302}{-800{,}526} = 0.9997 \quad \underline{1.000}$$

Theoretical performance

- The reversible work represent the maximum electrical energy and hence the electromotive force is the maximum and equals to E_{rev} ,
- Hence:

$W_{rev} = \Delta G = \text{(emf)(passing electrons)} = -E_{rev}I\tau$

Where I: current

τ: time for consuming one mole of fuel: time/kgmole.

- But $I\tau = Z$ Ŧ

Z: electrochemical valence or number of electrons released in a reaction.

And Ŧ : Faraday = 4.648×10^{7}coulombs/kgmole

Now $\Delta G = -E_{rev}I\,\tau = -E_{rev}Z$ Ŧ

See table 12.3 p(448) for values of Z & E_{rev}

Theoretical performance

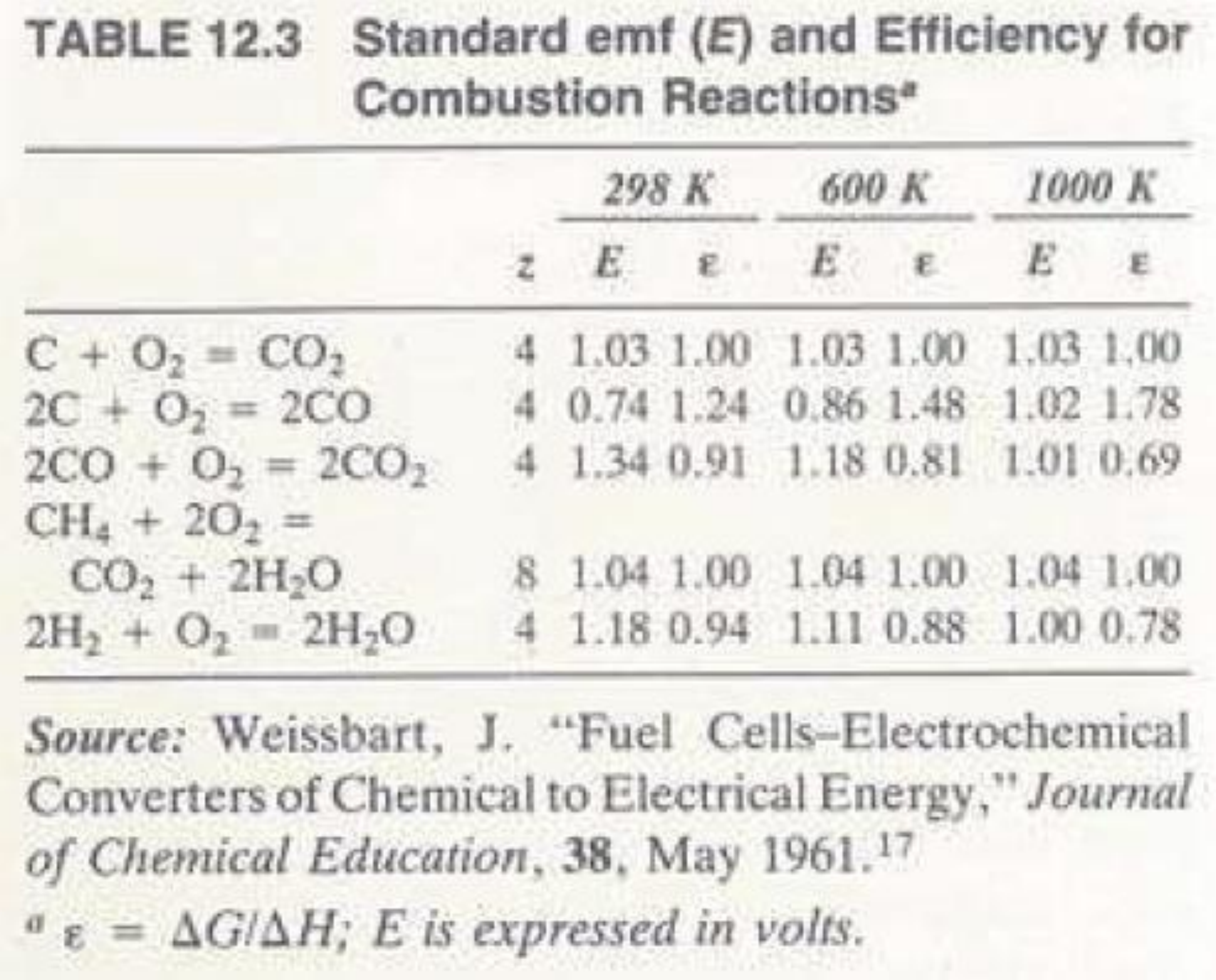


TABLE 12.3 Standard emf (*E*) and Efficiency for Combustion Reactions[a]

		298 K		600 K		1000 K	
	z	*E*	ε	*E*	ε	*E*	ε
$C + O_2 = CO_2$	4	1.03	1.00	1.03	1.00	1.03	1.00
$2C + O_2 = 2CO$	4	0.74	1.24	0.86	1.48	1.02	1.78
$2CO + O_2 = 2CO_2$	4	1.34	0.91	1.18	0.81	1.01	0.69
$CH_4 + 2O_2 = CO_2 + 2H_2O$	8	1.04	1.00	1.04	1.00	1.04	1.00
$2H_2 + O_2 = 2H_2O$	4	1.18	0.94	1.11	0.88	1.00	0.78

Source: Weissbart, J. "Fuel Cells–Electrochemical Converters of Chemical to Electrical Energy," *Journal of Chemical Education*, **38**, May 1961.[17]

[a] *ε = ΔG/ΔH; E is expressed in volts.*

Actual performance

- In actual cell, W_a is less than W_{rev}

Or $W_a < \Delta G$, and $W_a < \Delta H - T\,\Delta S$

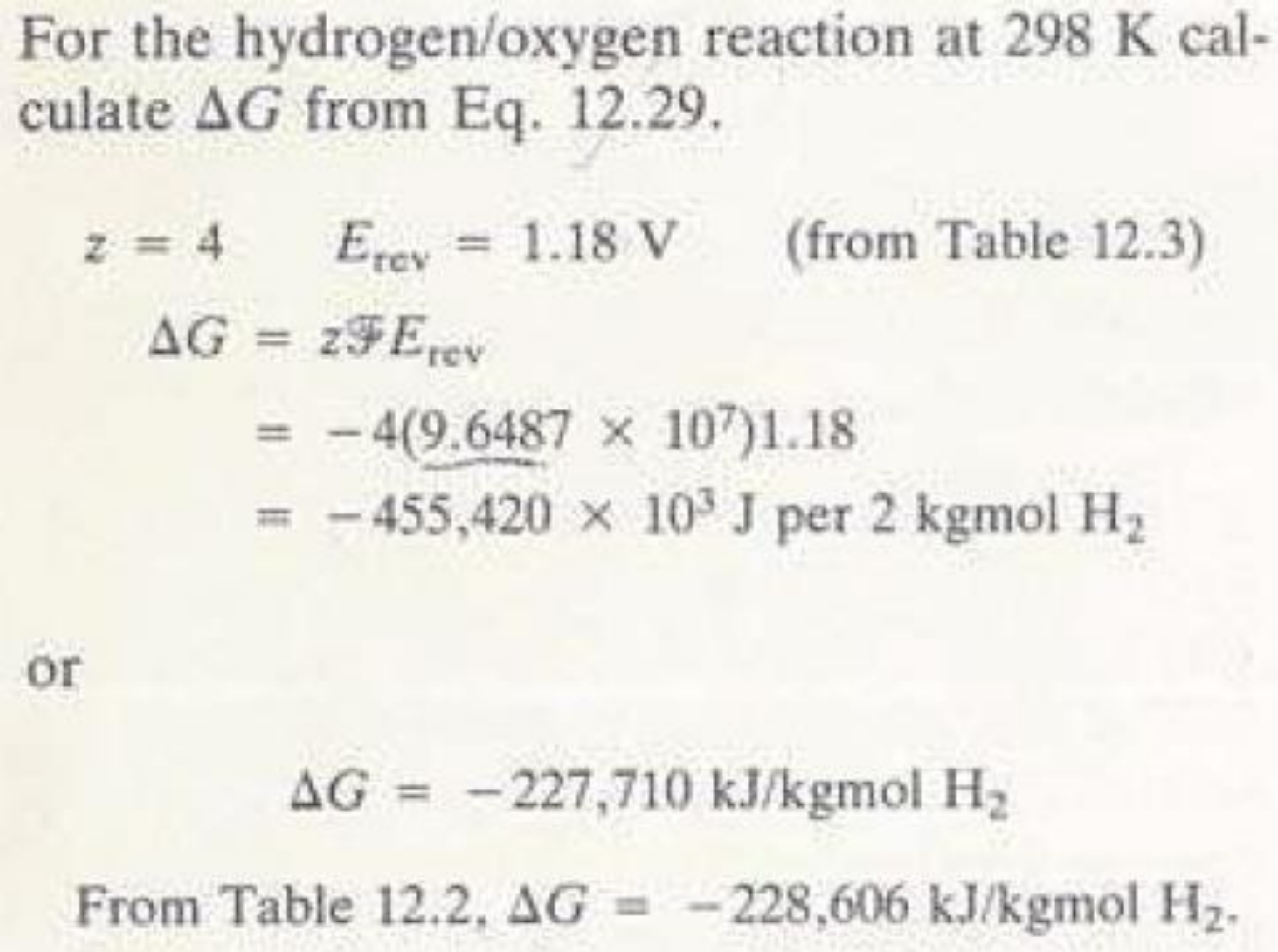
- Actually from first law $W_a = \Delta H - Q$
- Recall $dS \leq dQ/T \rightarrow Q \geq T\,\Delta S$ for isothermal process
- Also $W_a = -E_a I\,\tau = \Delta H - Q$

  Here E_a is the actual emf
- The actual conversion efficiency ε_a

  $\varepsilon_a = W_a / \Delta H = -E_a I\,\tau / \Delta H$
- The difference between theoretical reversible and actual (irreversible) fuel cell performance is expressed as:
- $E_{rev} I\tau - E_a I\,\tau = T\Delta S - Q$

  Or $E_a / E_{rev} < 1.0$

Examples 12.11



For the hydrogen/oxygen reaction at 298 K calculate ΔG from Eq. 12.29.

$$z = 4 \qquad E_{rev} = 1.18\ \text{V} \qquad \text{(from Table 12.3)}$$

$$\begin{aligned} \Delta G &= z\mathcal{F}E_{rev} \\ &= -4(9.6487 \times 10^7)1.18 \\ &= -455{,}420 \times 10^3\ \text{J per 2 kgmol H}_2 \end{aligned}$$

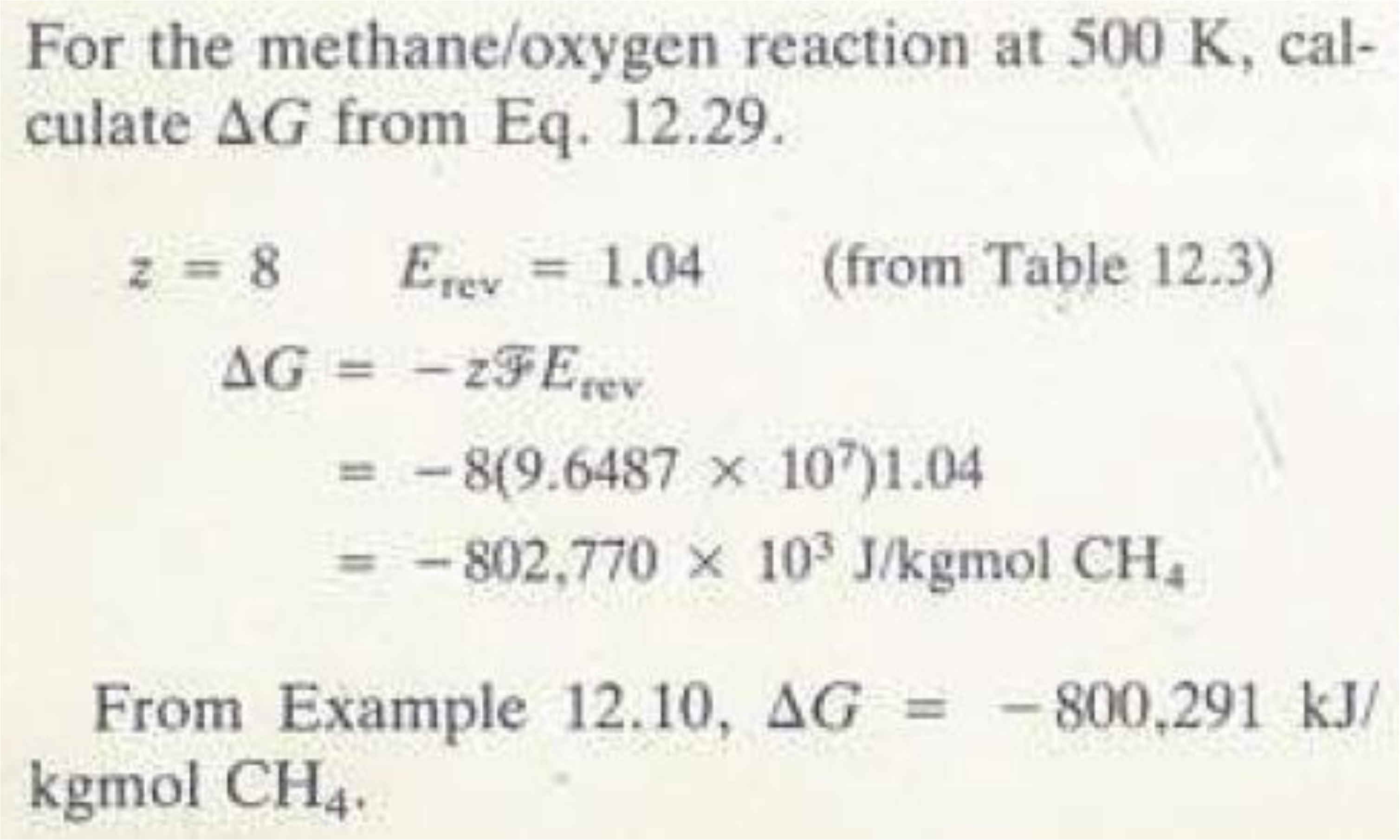
or

$$\Delta G = -227{,}710\ \text{kJ/kgmol H}_2$$

From Table 12.2, $\Delta G = -228{,}606$ kJ/kgmol H_2.

Cathode reaction O2 + 2H2O + 4e- CO2 + 4OH$^-$
Anode reaction 2H2 + 4OH$^-$ 4H2O + 4e-
Overall reaction O2 + 2H2 2H2O

Example 12.12



For the methane/oxygen reaction at 500 K, calculate ΔG from Eq. 12.29.

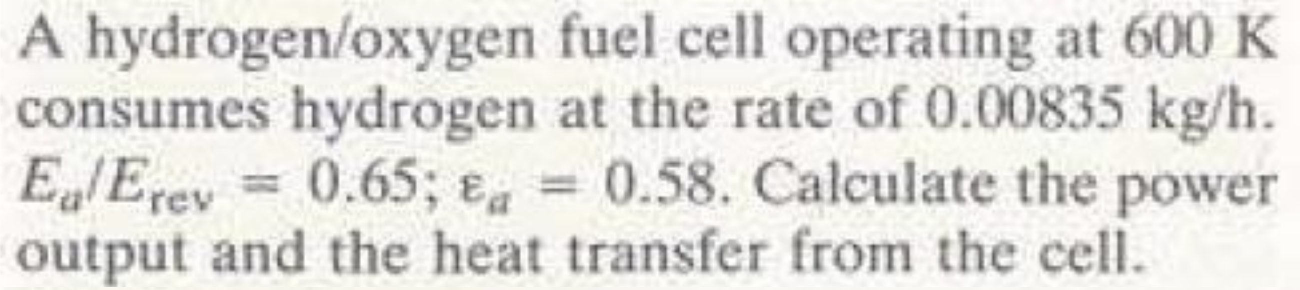
$$z = 8 \qquad E_{rev} = 1.04 \qquad \text{(from Table 12.3)}$$

$$\begin{aligned} \Delta G &= -z\mathcal{F}E_{rev} \\ &= -8(9.6487 \times 10^7)1.04 \\ &= -802{,}770 \times 10^3 \text{ J/kgmol } CH_4 \end{aligned}$$

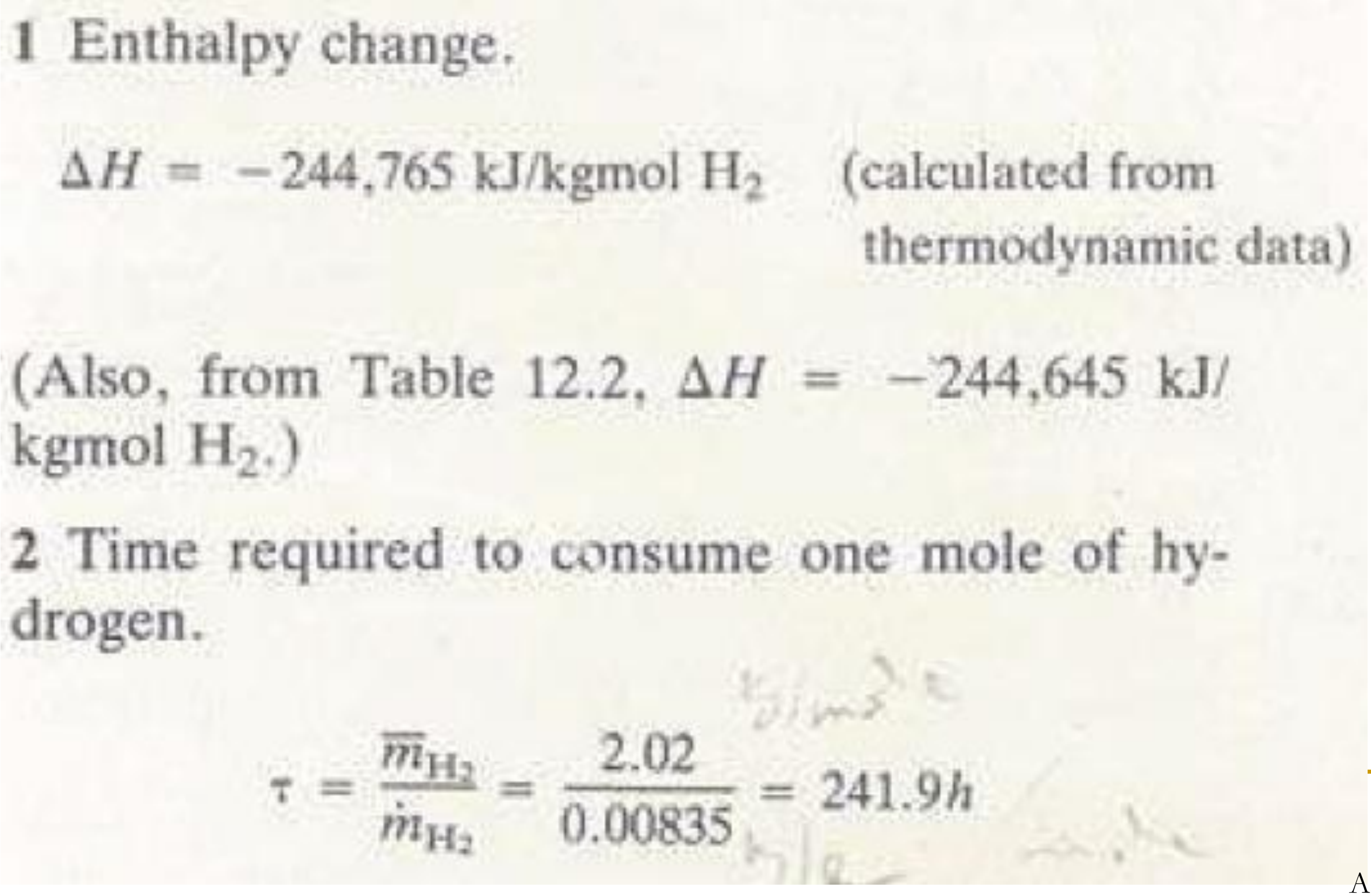
From Example 12.10, $\Delta G = -800{,}291$ kJ/kgmol CH_4.

$$CH4 \quad + \quad 2O2 \quad \longrightarrow \quad CO2 \quad + \quad 2H2O$$

Example 12.13



A hydrogen/oxygen fuel cell operating at 600 K consumes hydrogen at the rate of 0.00835 kg/h. $E_a/E_{rev} = 0.65$; $\varepsilon_a = 0.58$. Calculate the power output and the heat transfer from the cell.



1 Enthalpy change.

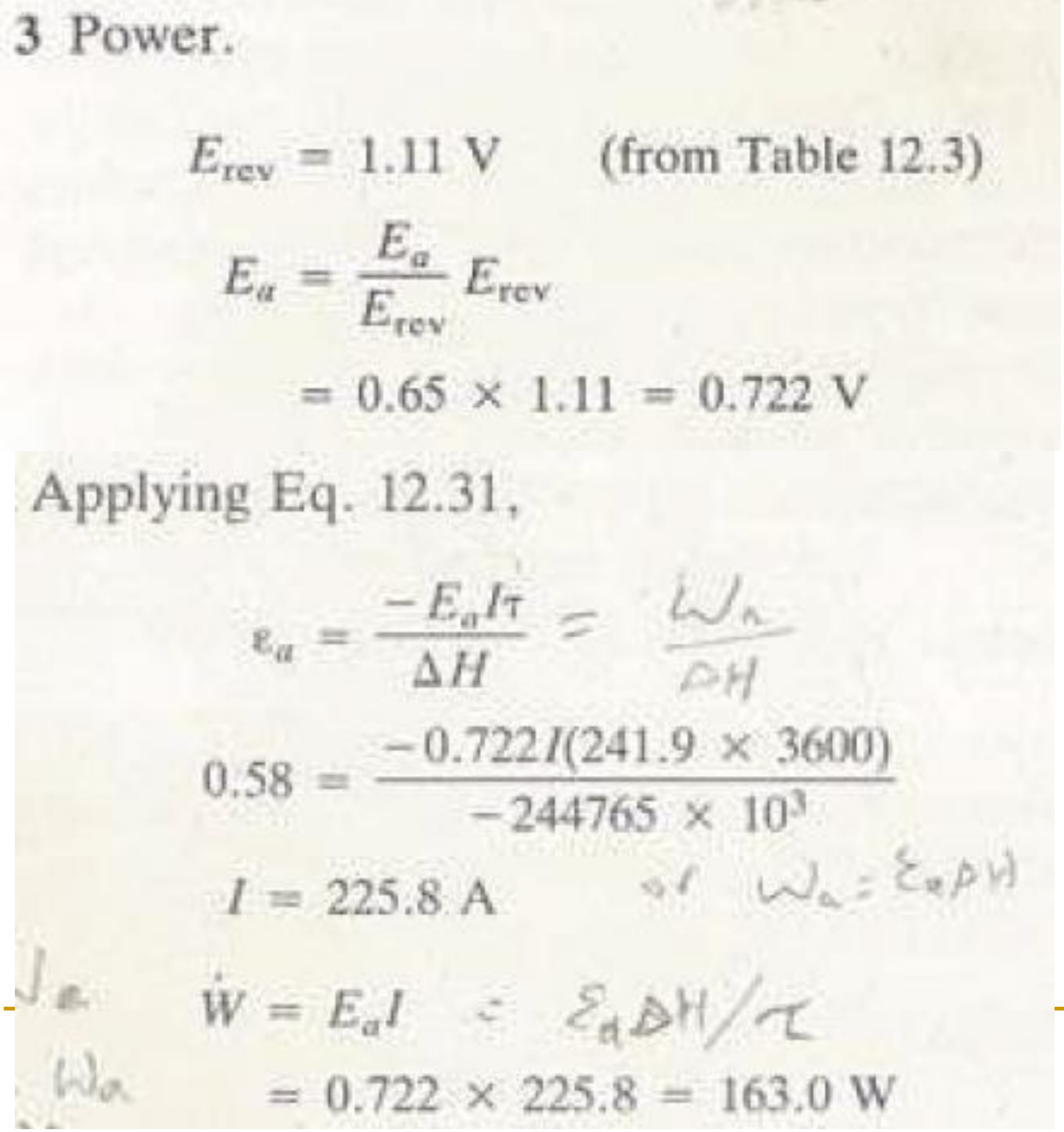
$$\Delta H = -244{,}765 \text{ kJ/kgmol H}_2 \quad \text{(calculated from thermodynamic data)}$$

(Also, from Table 12.2, $\Delta H = -244{,}645$ kJ/kgmol H_2.)

2 Time required to consume one mole of hydrogen.

$$\tau = \frac{\overline{m}_{H_2}}{\dot{m}_{H_2}} = \frac{2.02}{0.00835} = 241.9h$$

Example 12.13



3 Power.

$$E_{rev} = 1.11 \text{ V} \qquad \text{(from Table 12.3)}$$

$$E_a = \frac{E_a}{E_{rev}} E_{rev}$$

$$= 0.65 \times 1.11 = 0.722 \text{ V}$$

Applying Eq. 12.31,

$$\varepsilon_a = \frac{-E_a I\tau}{\Delta H} = \frac{W_a}{\Delta H}$$

$$0.58 = \frac{-0.722 I(241.9 \times 3600)}{-244765 \times 10^3}$$

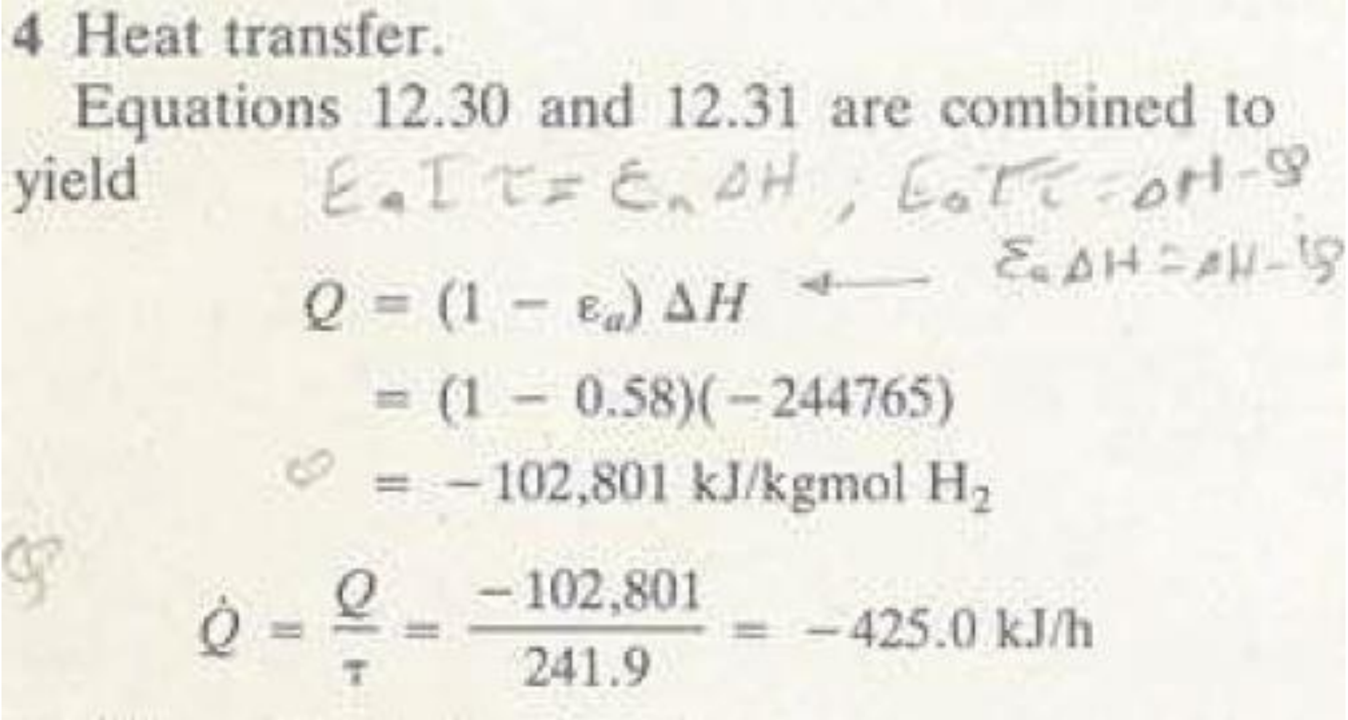
$$I = 225.8 \text{ A} \qquad \text{or} \quad W_a = \varepsilon_a \Delta H$$

$$\dot{W} = E_a I = \varepsilon_a \Delta H / \tau$$

W_a

$$= 0.722 \times 225.8 = 163.0 \text{ W}$$

Example 12.13



4 Heat transfer.

Equations 12.30 and 12.31 are combined to yield $\varepsilon_a I \tau = \varepsilon_n \Delta H$, $\varepsilon_a I \tau = \Delta H - Q$

$$Q = (1 - \varepsilon_a)\,\Delta H \longleftarrow \varepsilon_a \Delta H = \Delta H - Q$$

$$= (1 - 0.58)(-244765)$$

$$= -102{,}801 \text{ kJ/kgmol } H_2$$

$$\dot{Q} = \frac{Q}{\tau} = \frac{-102{,}801}{241.9} = -425.0 \text{ kJ/h}$$

Outline

- Introduction
- Topping and tailing
- MHD
- Thermoelectric
- Thermionic
- Fuel cell
  - Principle
  - Types
  - Performance
  - Applications
- Photovoltaic

Fuel cell applications

- Many factors are to be considered when selecting fuel cell as a power source including cost, reactivity and weight.
- Automobile applications: unlikely to replace ICE since the cost is higher. CH4 or propane fuel could be used.
- Space applications: very likely since it avoids cooling problems and supply water in addition to power.
- Utility companies: A fuel cell generator rating 25 MW power is experimented in USA. It is an assembly of fuel cells each of 1 volt with 1-2 kW per m^2 of electrode area. The advantages include no pollution, no sitting problems, it can be employed in different locations where it is needed and connected to the utility network.

Fuel cell applications

- For automotive applications fuel cells are only suited to hybrid applications for providing the base power load with the demand peaks.
- Fuel cells have been used successfully in aerospace applications.
- Simple low power demonstrator kits are available for education purposes.
- Perhaps the best applications for fuel cells will be for high power load levelling.
- Prototypes of Direct Methanol cells are currently being trialed for mobile phone and laptop computer applications

Outline

- Introduction
- Topping and tailing
- MHD
- Thermoelectric
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- Fuel cell
- Photovoltaic

Photovoltaic Power

- Photovoltaic (PV) is the technology of converting light directly to electrical energy.
- Solar cells, which are large-area diodes of semiconductor materials, are used as energy converters.
- When light is absorbed by the semiconductor material, an electric potential is built up at the metallic contacts of the diode. Current flows once a load is connected.
- The absorbed energy has been converted to electrical energy.
- The ratio of the electrical energy produced to the incident radiant energy is called the efficiency of the solar cell.

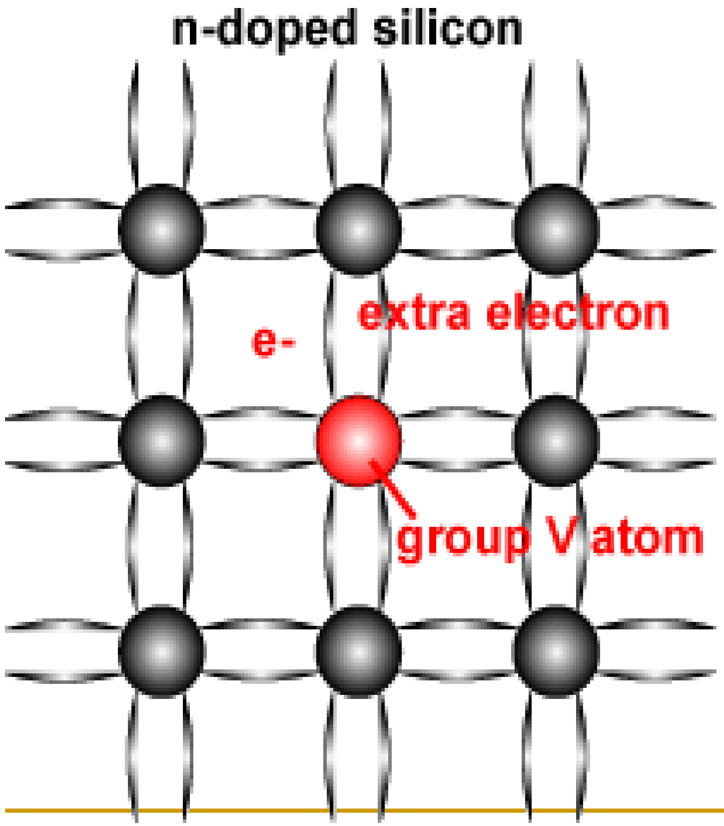
semiconductor materials

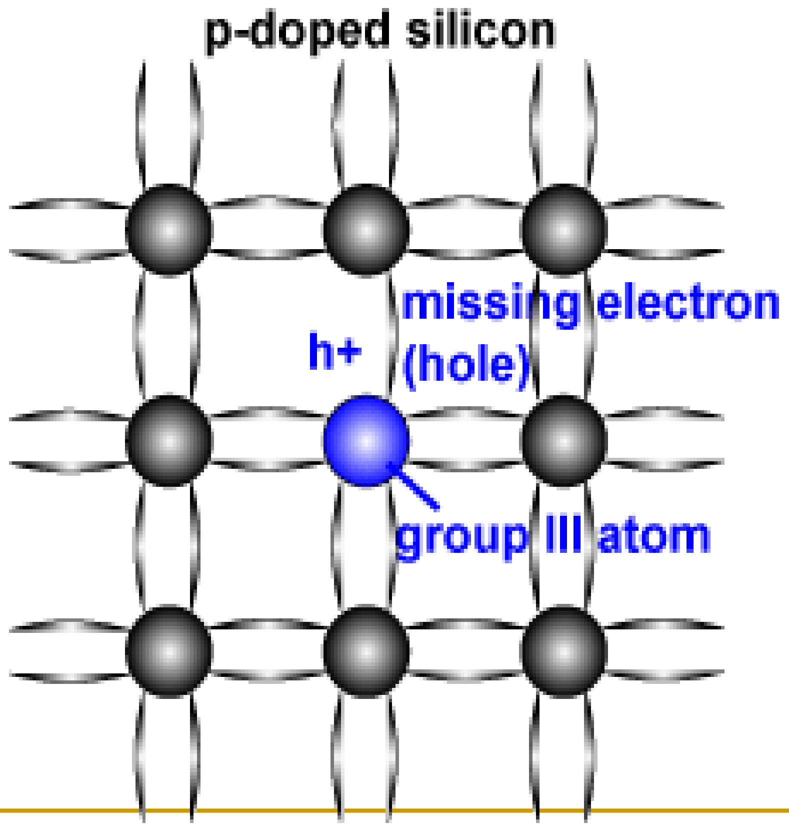
- Silicon is a poor electrical conductor. It becomes conductive by the process of doping.
- The addition of traces of phosphorus or arsenic elements makes it conductive by creating negative charges and forming n-type semiconductor.
- The addition of traces of boron to the silicon creates positive charges and therefore forms the p-type semiconductor.
- The silicon cell is formed by making a junction between the two different semiconductors n/p.

Doping

Traces of phosphorus elements makes creates negative charges and forming n-type semiconductor

Traces of boron to the silicon creates positive charges and forms the p-type semiconductor.





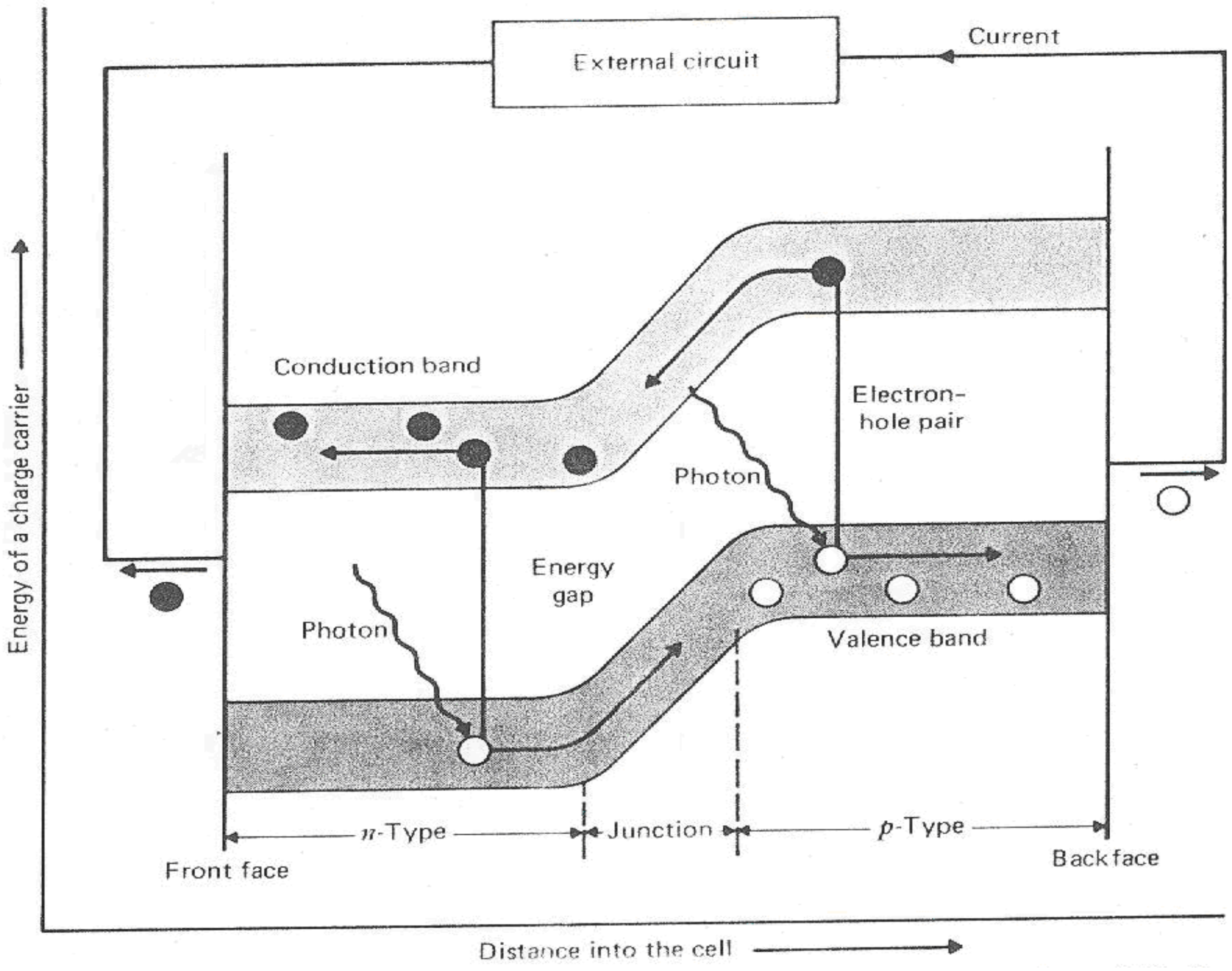
Energy levels and gap

- In semiconductor material, electrons occupy one of two energy band levels separated by an energy gap: The low energy level (valence level) is nearly filled with electrons while the higher energy level (conduction band) is empty or slightly occupied.
- Some of solar photons are absorbed in the vicinity of the n/p junction gaining energy and moving to the higher conduction band hence leaving holes behind, thus creating electron hole pairs.
- When external load is connected, electrons flow from front surface (n-type) to back surface (p-type) forming an electric current.

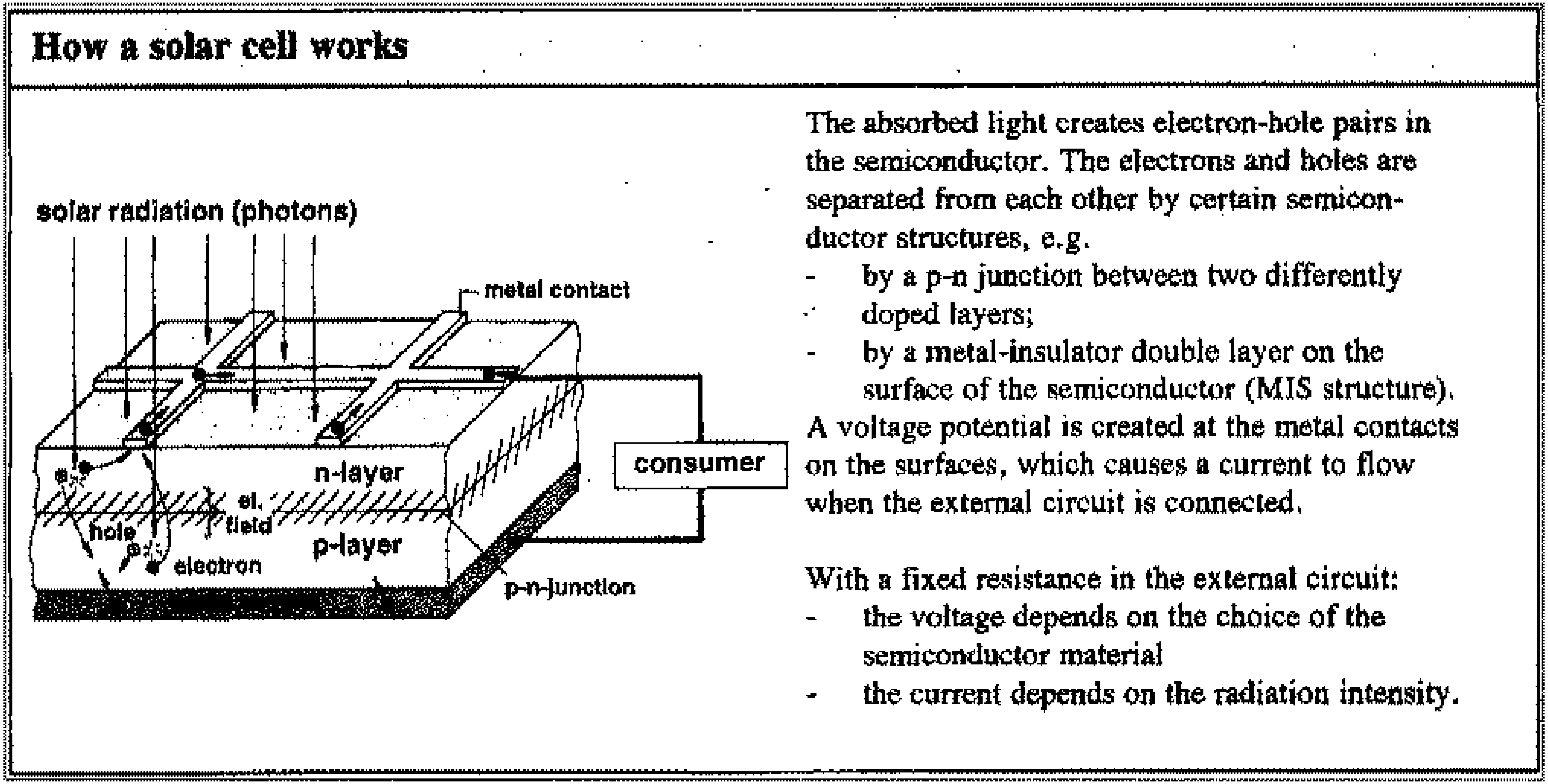
Band gap

- The **band gap** of a semiconductor is the minimum energy required to move an electron from its bound state to a free state where it can participate in conduction.
- The lower energy level of a semiconductor is called the "valence band" (EV) and the energy level at which an electron can be considered free is called the "conduction band" (EC).
- The band gap (EG) is the distance between the conduction band and valence band.

Schematic of the energy bands for electrons in a solid



Solar cell



How a solar cell works

The absorbed light creates electron-hole pairs in the semiconductor. The electrons and holes are separated from each other by certain semiconductor structures, e.g.

- by a p-n junction between two differently doped layers;
- by a metal-insulator double layer on the surface of the semiconductor (MIS structure).

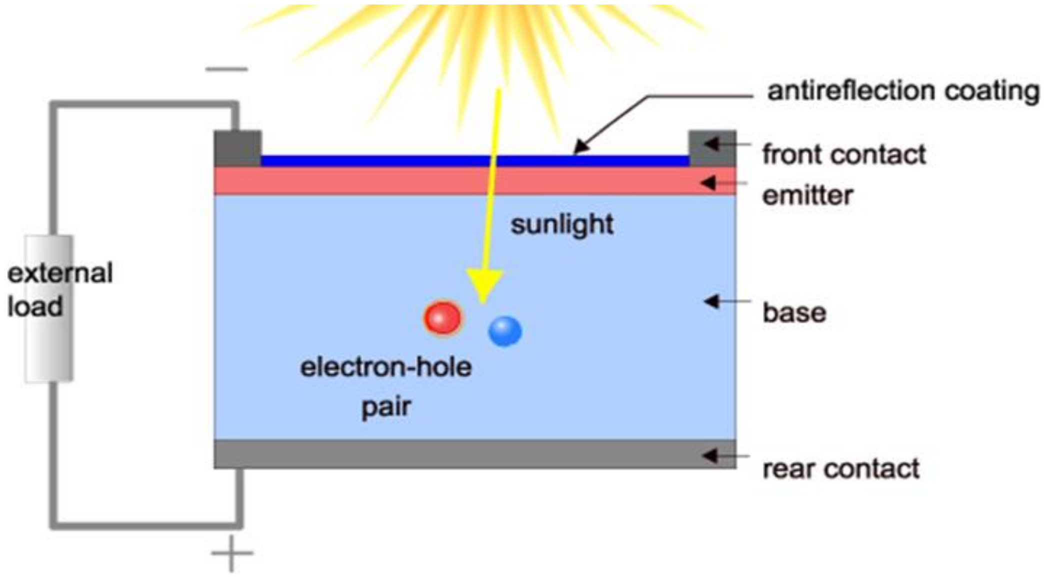
A voltage potential is created at the metal contacts on the surfaces, which causes a current to flow when the external circuit is connected.

With a fixed resistance in the external circuit:

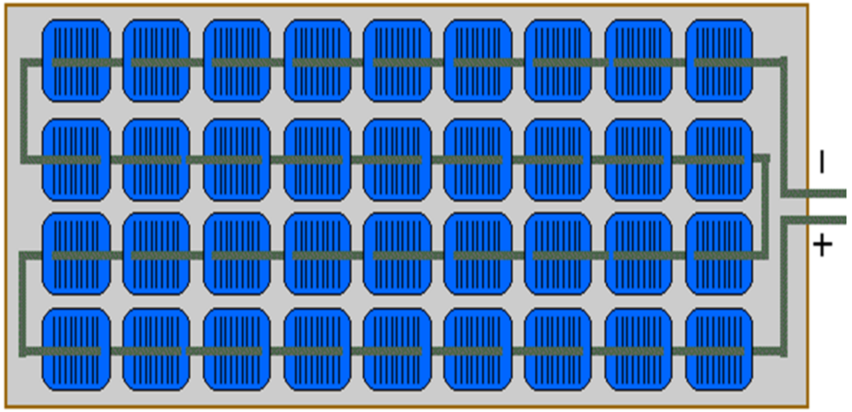
- the voltage depends on the choice of the semiconductor material
- the current depends on the radiation intensity.

Solar cell

- In order to supply more power, single solar cells are combined to form modules.
- When solar cells are made of crystalline wafers are used, contacts are made on the individual cells and these are soldered or welded together into strings.



A typical module has 36 cells in series



Advantages & disadvantages

- Advantages:
  - Clean, no pollution or noise.
  - Free of operation and maintenance cost since no moving parts.
  - Light weight: power/mass is relatively high, compact.
- Disadvantages of PV:
  - High cost
  - Low efficiency: $\mu_{max} = 22\%$, practically $\mu \leq 15\%$.
  - It needs energy storage because of intermittence of solar radiation.

Photovoltaic cell performance

- When a load is connected to the cell portion of the current generated by the PV is shunted through the internal cell resistance, R_J . The shunted current through the junction

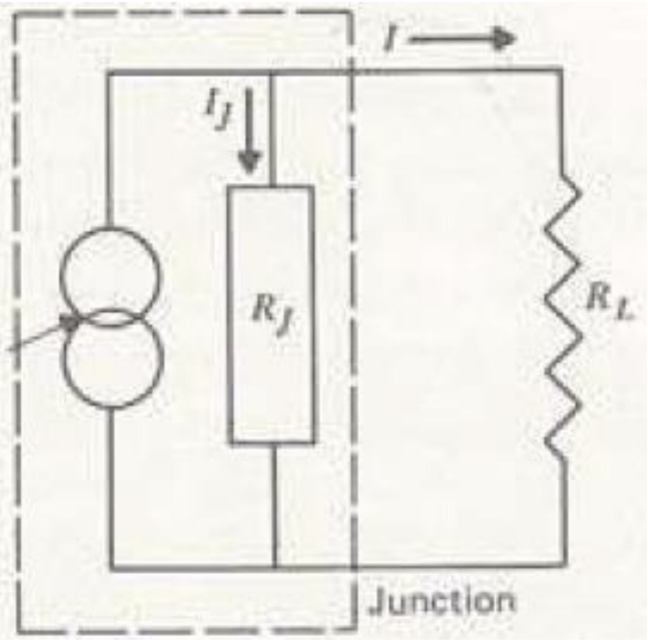
$$Ij = Io[e^{\frac{eV}{kT}} - 1]$$

Where V: applied voltage to the cell.

Io: reverse saturation or dark current, which is the current that flows when a large reverse bias is applied across the junction, and the current is due to only minority carriers.

e = 1.602×10^{-19} coulombs or J/V.

k = Boltzman constant = 1.381×10^{-23} J/K



Photovoltaic cell performance

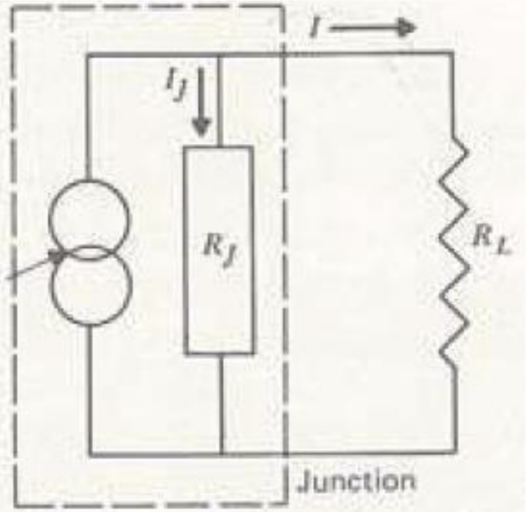
- The current through the external load I_L is given as:

  $I_L = I_{sc} – Ij = I_{sc} – Io[\exp(eV/kT) – 1]$

  Where I_{sc} : the short circuit current.
- Note: for short circuit V=0 and $I_L = I_{sc}$

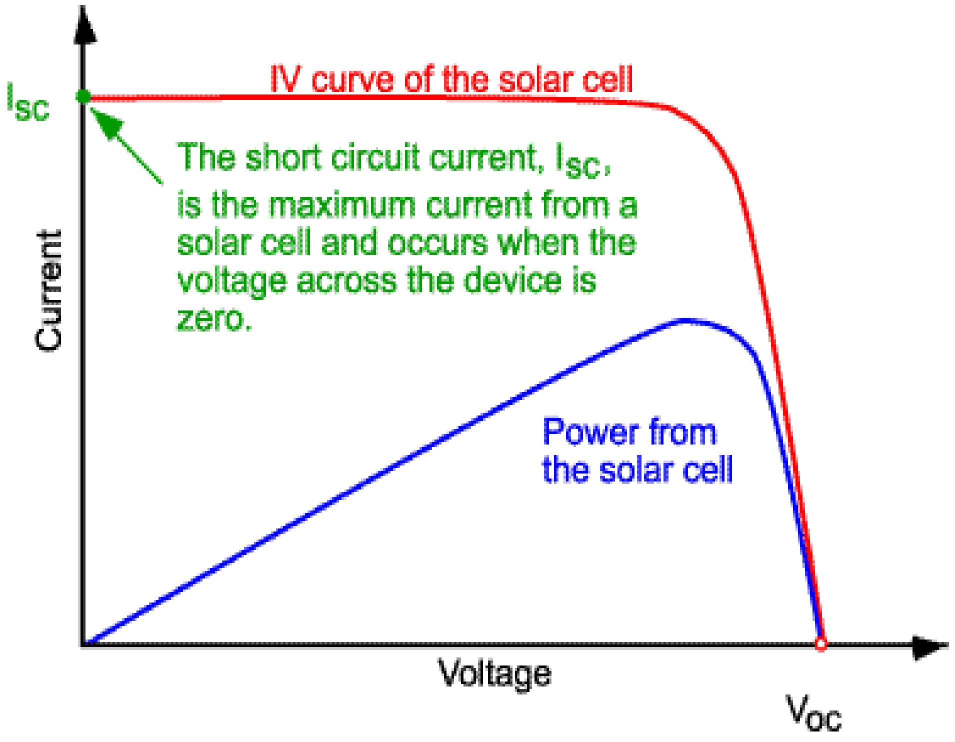
  For open circuit I_L =0 and V=Voc
- For open circuit $I_L =0 = I_{sc} – Io[\exp(eVoc/kT) –1]$

  $Voc = (kT/e) \ln (I_{sc} /Io +1)$
- The power $P= I_L V = I_L^2 R_L$



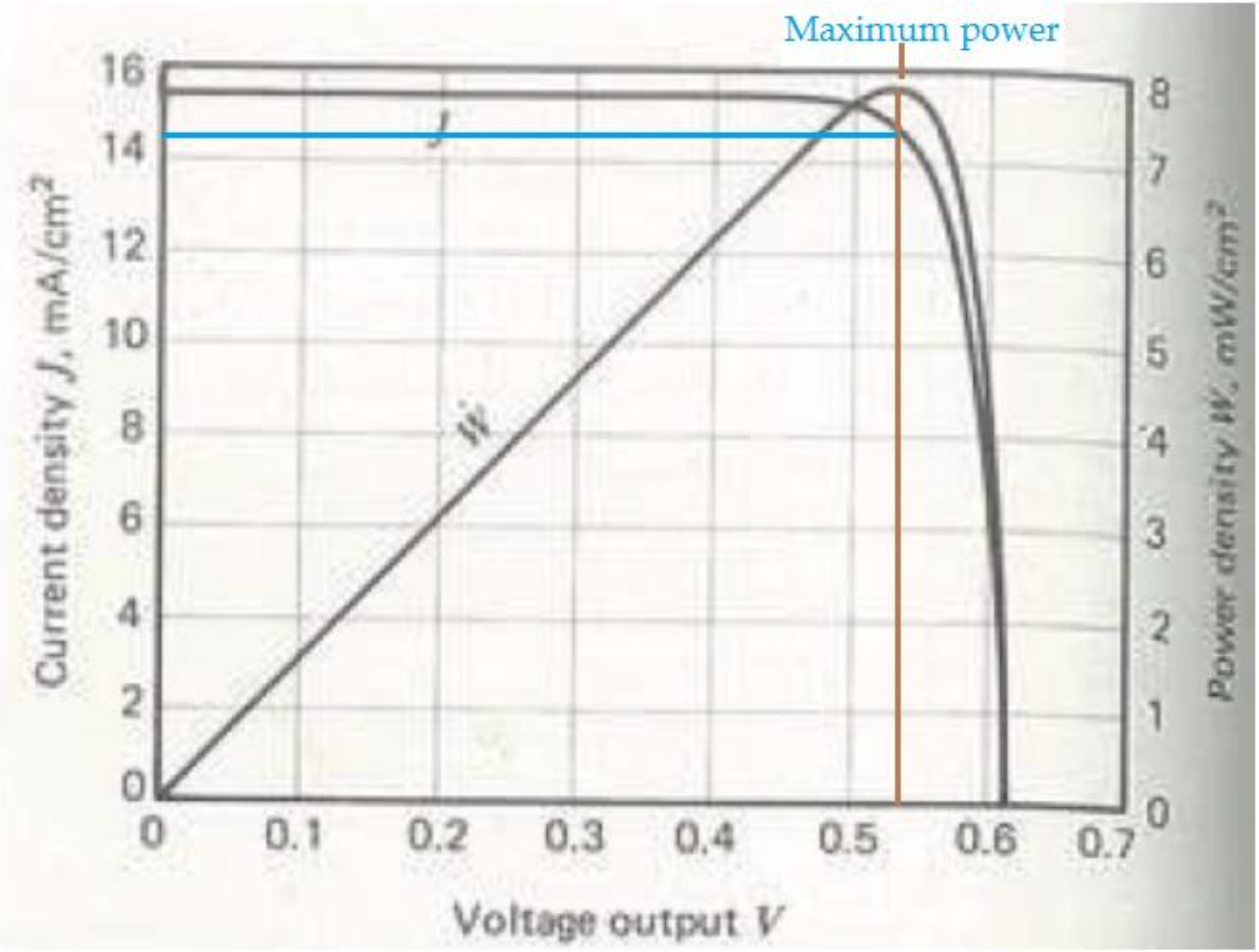
I-V curve for solar cell

- **short-circuit current** is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as I_{SC}
- The open-circuit voltage, Voc, is the maximum voltage available from a solar cell, and this occurs at zero current.



$$Voc = (kT/e)\ln(I_{sc}/Io + 1)$$

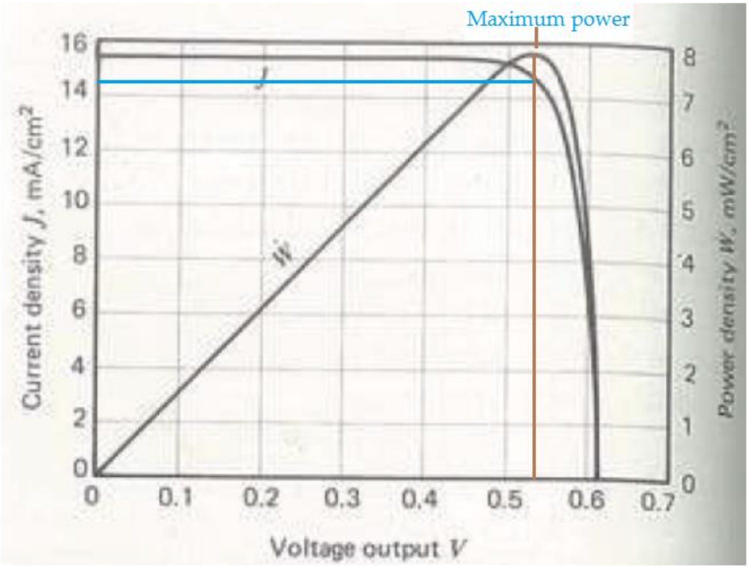
I-V curve for solar cell



Maximum power

- The power output exhibits a maximum, to find the condition for the maximum power output P_{max},
- $dP_{max}/dV = 0$, Then $\exp(eV_{mp}/kT) = (Js/Jo + 1)/(eV_{mp}/kT + 1)$
- current density at maximum power;

  $J_{mp} = (Js + Jo)/(kT/eV_{mp} + 1)$
- $P_{max} = AJ_{mp}V_{mp} = [V_{mp}(Js + Jo)A]/(kT/eV_{mp} + 1)$



Conversion efficiency

- Conversion efficiency of the cell:

  η = power / solar power in

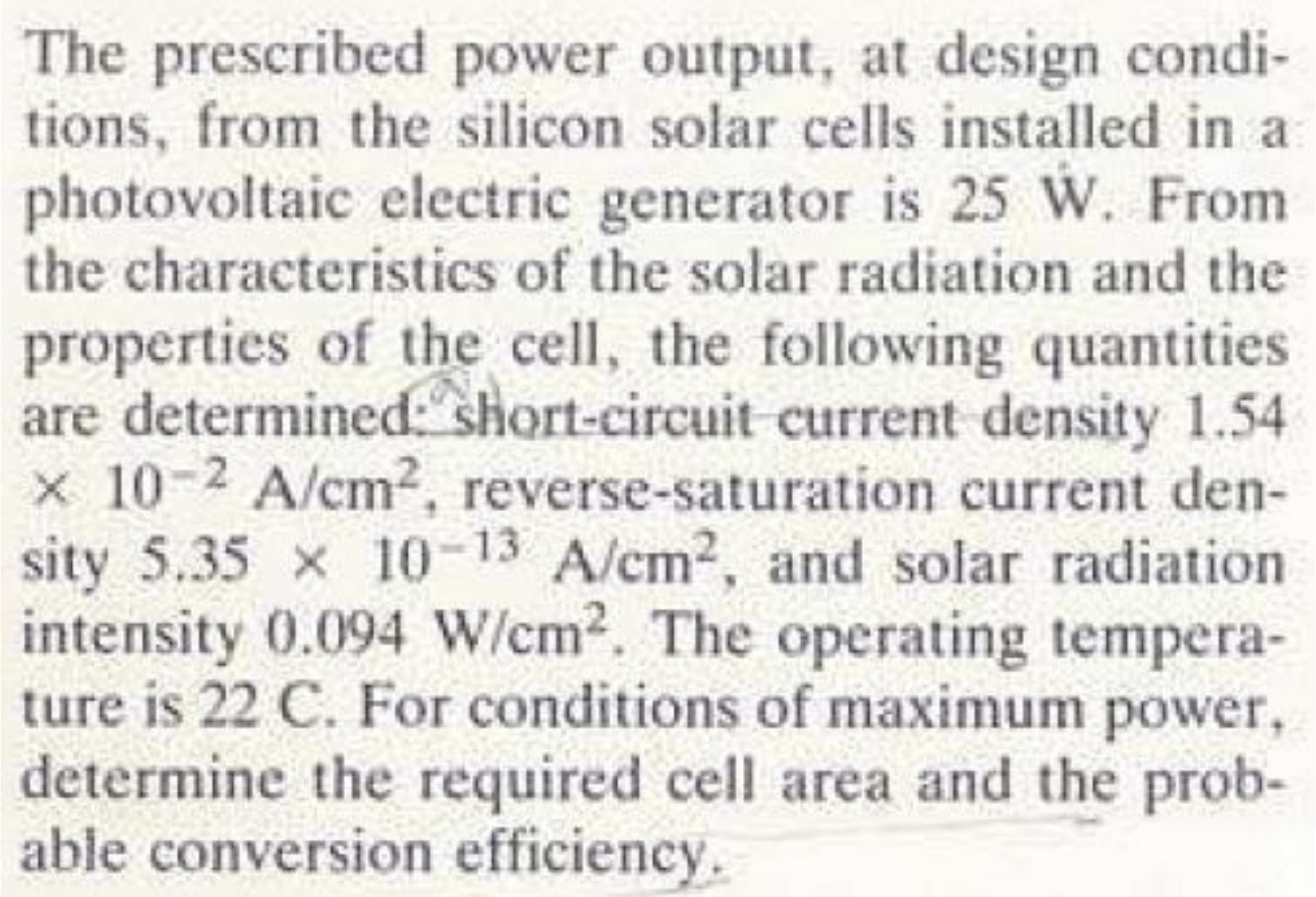
  $\eta = P/A\, E_{solar}$
- At maximum power:

  $\eta_{mp}=[V_{mp}\,(Js + Jo)/\,[(\,kT\,/eV_{mp} + 1)]]/AE_{solar}$

  So $P_{max} = \eta AE_{solar}$

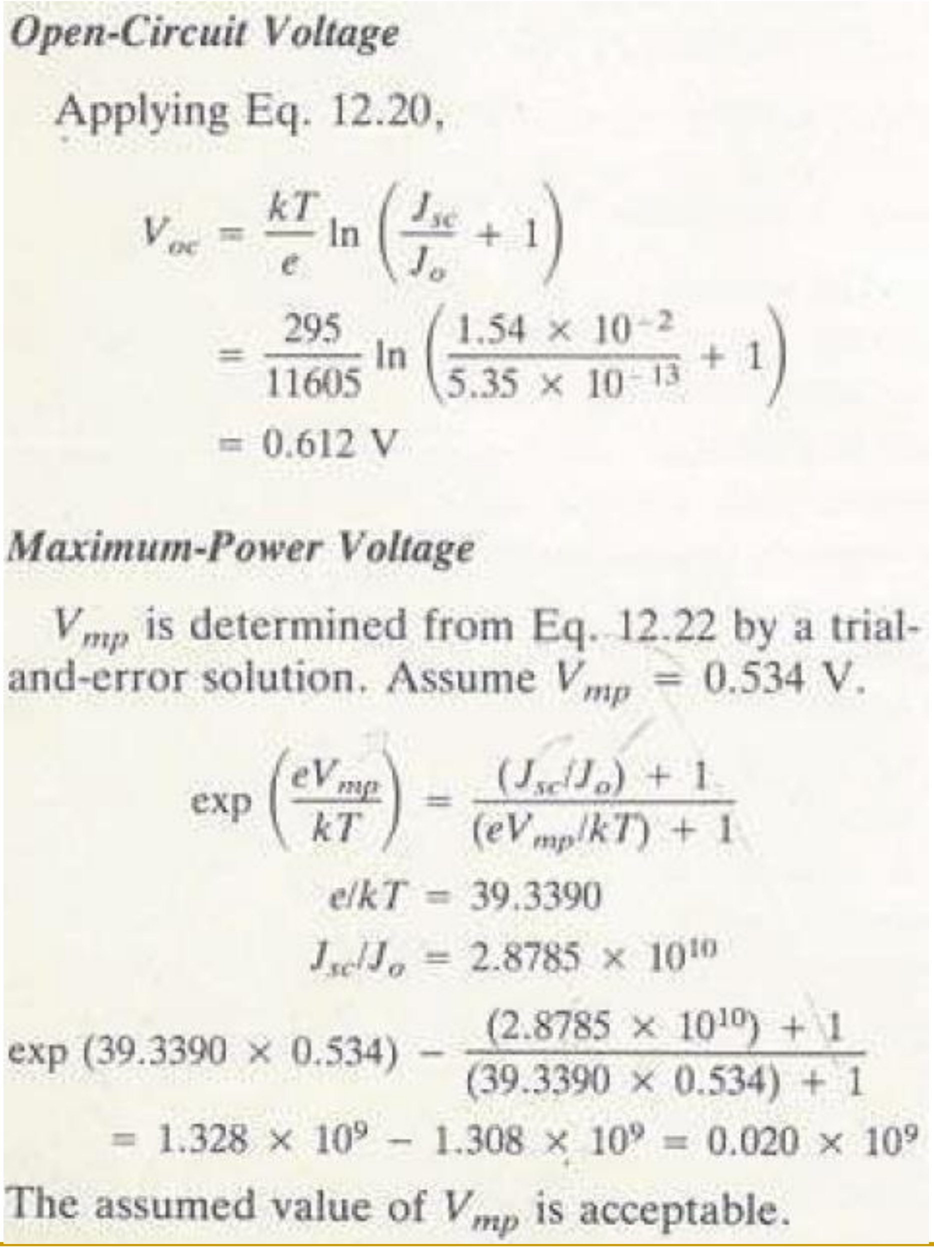
Efficiency of solar cells: theoretical limitation on the efficiency of solar cell can be calculated. However practical efficiencies are much lower.

Example 12.7



The prescribed power output, at design conditions, from the silicon solar cells installed in a photovoltaic electric generator is 25 $\dot{W}$. From the characteristics of the solar radiation and the properties of the cell, the following quantities are determined: short-circuit current density 1.54 × 10^{-2} A/cm^2, reverse-saturation current density 5.35 × 10^{-13} A/cm^2, and solar radiation intensity 0.094 W/cm^2. The operating temperature is 22 C. For conditions of maximum power, determine the required cell area and the probable conversion efficiency.

Example 12.7



Open-Circuit Voltage

Applying Eq. 12.20,

$$V_{oc} = \frac{kT}{e} \ln\left(\frac{J_{sc}}{J_o} + 1\right)$$

$$= \frac{295}{11605} \ln\left(\frac{1.54 \times 10^{-2}}{5.35 \times 10^{-13}} + 1\right)$$

$$= 0.612 \text{ V}$$

Maximum-Power Voltage

V_{mp} is determined from Eq. 12.22 by a trial-and-error solution. Assume $V_{mp} = 0.534$ V.

$$\exp\left(\frac{eV_{mp}}{kT}\right) = \frac{(J_{sc}/J_o) + 1}{(eV_{mp}/kT) + 1}$$

$$e/kT = 39.3390$$

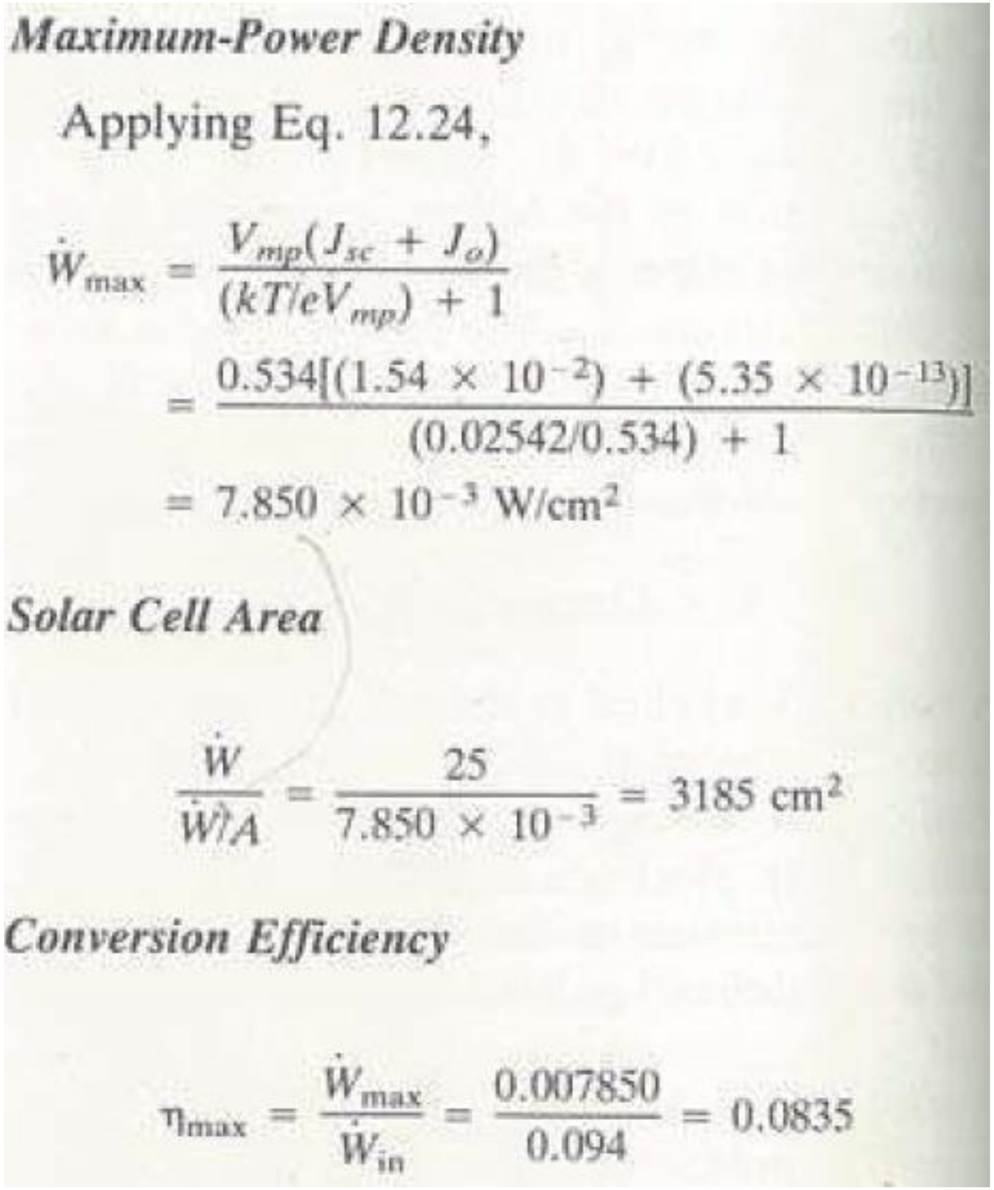
$$J_{sc}/J_o = 2.8785 \times 10^{10}$$

$$\exp(39.3390 \times 0.534) - \frac{(2.8785 \times 10^{10}) + 1}{(39.3390 \times 0.534) + 1}$$

$$= 1.328 \times 10^9 - 1.308 \times 10^9 = 0.020 \times 10^9$$

The assumed value of V_{mp} is acceptable.

Example 12.7



Maximum-Power Density

Applying Eq. 12.24,

$$\dot{W}_{\max} = \frac{V_{mp}(J_{sc} + J_o)}{(kT/eV_{mp}) + 1}$$

$$= \frac{0.534[(1.54 \times 10^{-2}) + (5.35 \times 10^{-13})]}{(0.02542/0.534) + 1}$$

$$= 7.850 \times 10^{-3}\ \mathrm{W/cm^2}$$

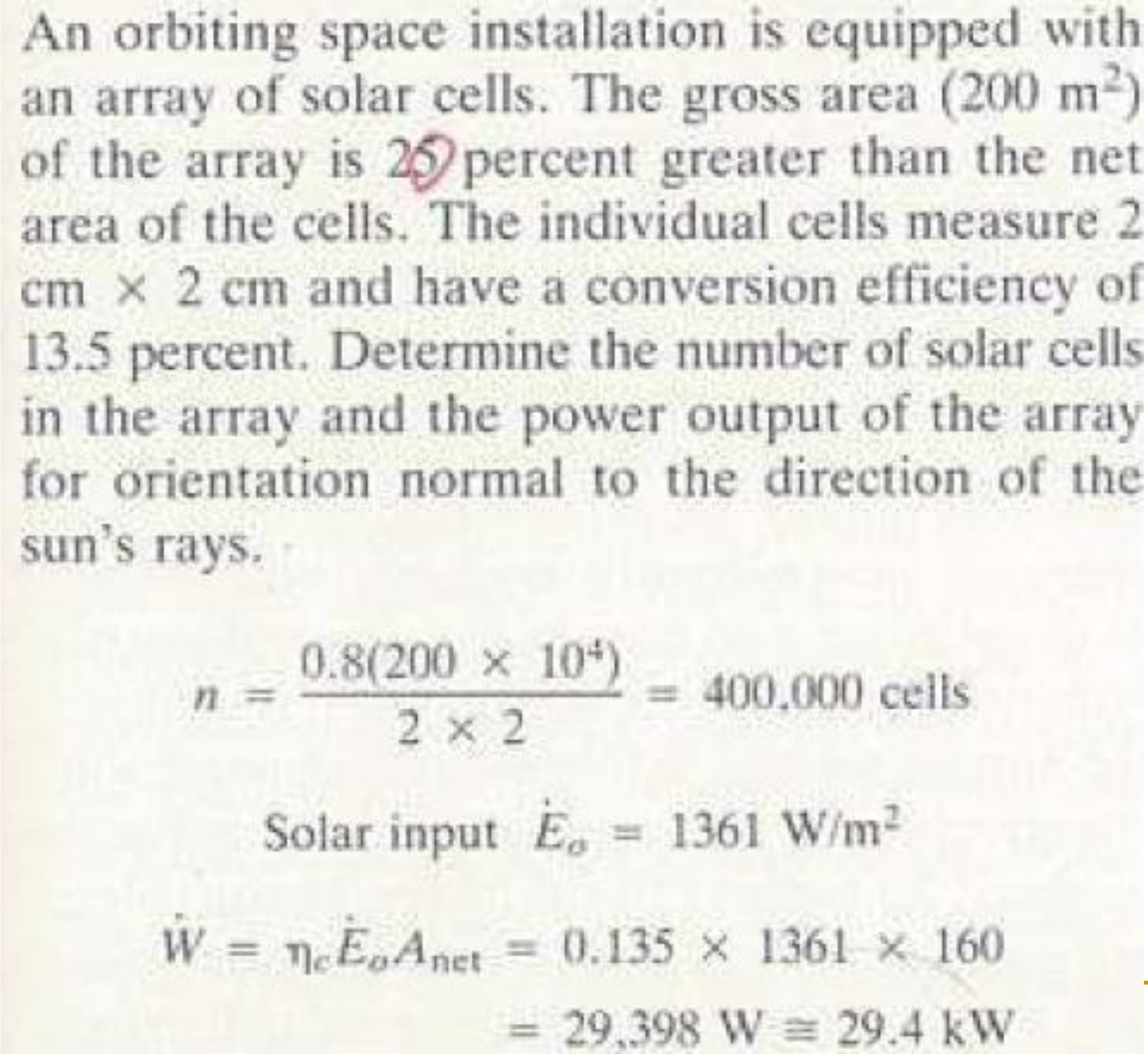
Solar Cell Area

$$\frac{\dot{W}}{\dot{W}/A} = \frac{25}{7.850 \times 10^{-3}} = 3185\ \mathrm{cm^2}$$

Conversion Efficiency

$$\eta_{\max} = \frac{\dot{W}_{\max}}{\dot{W}_{\text{in}}} = \frac{0.007850}{0.094} = 0.0835$$

Example 12.8



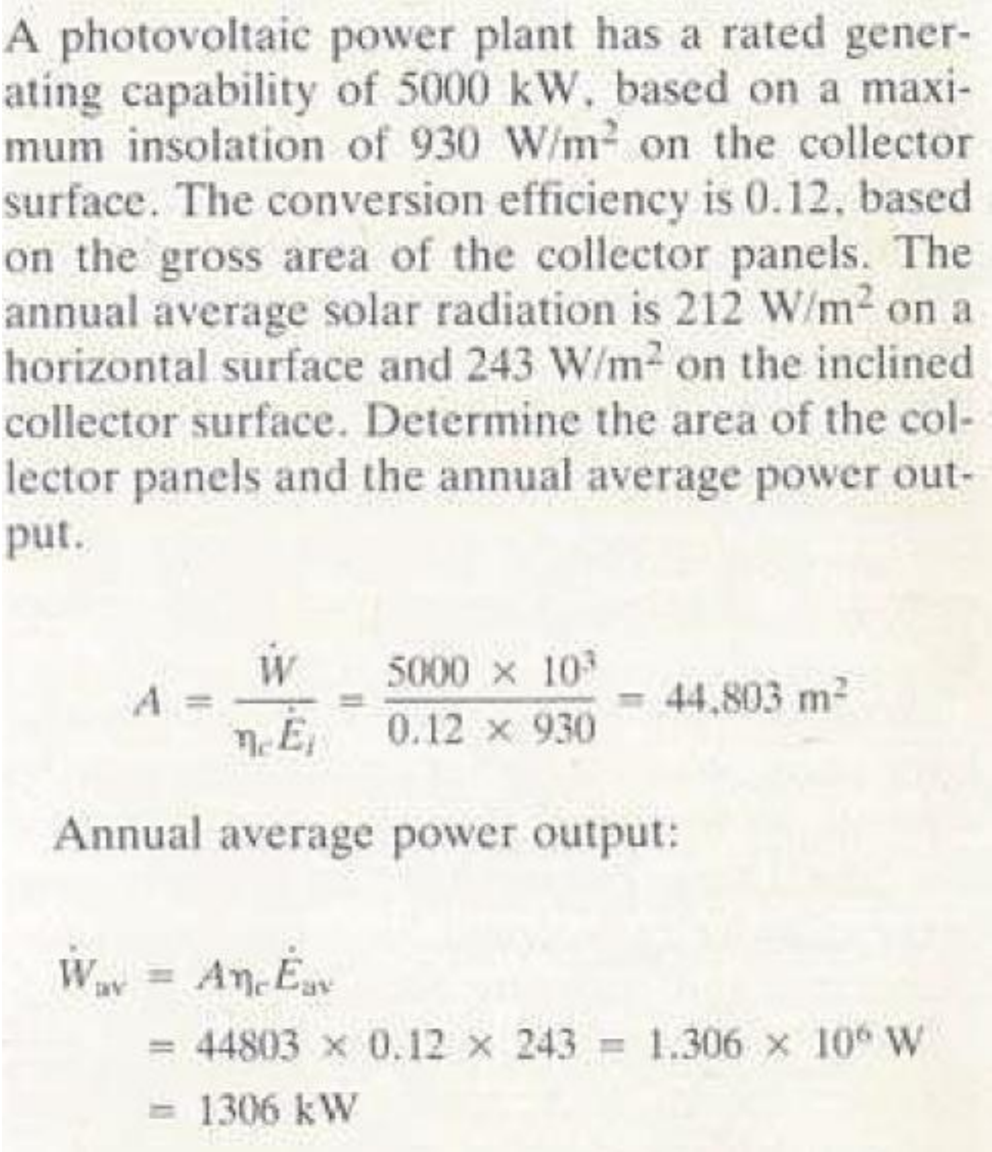
An orbiting space installation is equipped with an array of solar cells. The gross area (200 m^2) of the array is 25 percent greater than the net area of the cells. The individual cells measure 2 cm × 2 cm and have a conversion efficiency of 13.5 percent. Determine the number of solar cells in the array and the power output of the array for orientation normal to the direction of the sun's rays.

$$n = \frac{0.8(200 \times 10^4)}{2 \times 2} = 400{,}000 \text{ cells}$$

$$\text{Solar input} \quad \dot{E}_o = 1361 \text{ W/m}^2$$

$$\dot{W} = \eta_c \dot{E}_o A_{\text{net}} = 0.135 \times 1361 \times 160$$
$$= 29{,}398 \text{ W} \cong 29.4 \text{ kW}$$

Example 12.9



A photovoltaic power plant has a rated generating capability of 5000 kW, based on a maximum insolation of 930 W/m^2 on the collector surface. The conversion efficiency is 0.12, based on the gross area of the collector panels. The annual average solar radiation is 212 W/m^2 on a horizontal surface and 243 W/m^2 on the inclined collector surface. Determine the area of the collector panels and the annual average power output.

$$A = \frac{\dot{W}}{\eta_c \dot{E}_l} = \frac{5000 \times 10^3}{0.12 \times 930} = 44{,}803 \text{ m}^2$$

Annual average power output:

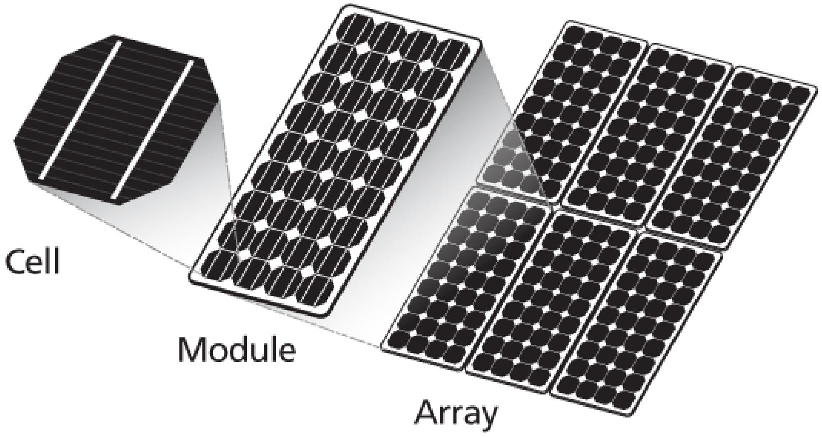
$$\begin{aligned} \dot{W}_{av} &= A\eta_c \dot{E}_{av} \\ &= 44803 \times 0.12 \times 243 = 1.306 \times 10^6 \text{ W} \\ &= 1306 \text{ kW} \end{aligned}$$

Cells –Modules- arrays

Number of individual PV cells are interconnected together in a sealed, weatherproof package called a Panel or Module. For example, a 12 V Panel (Module) will have 36 cells connected in series .

To achieve the desired voltage and current, Modules are wired in series and parallel into what is called a PV Array.

The flexibility of the modular PV system allows designers to create solar power systems that can meet a wide variety of electrical needs.



Testing and rating of PV

- PV cells and modules are tested under standard conditions of 1 kW/m^2 and power is reported as Wp.
- If solar radiation is then different then power is calculated as;

$$P_{actual} = Prated * \frac{E_{solar}\, kW/m^2}{1kW/m^2}$$

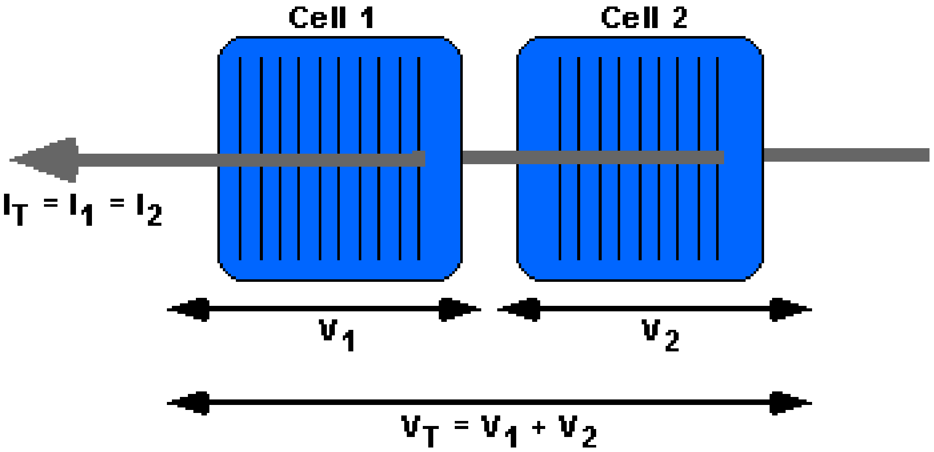
- e.g 100 Watt module will deliver only 60 Watt if solar radiation is 600W/m^2.

Cells in series

Since the cells are in series, the currents will be matched (not a problem as they are identical), voltages will add.

*typical voltages for a single solar cell wi*ll be < 0.6 V.

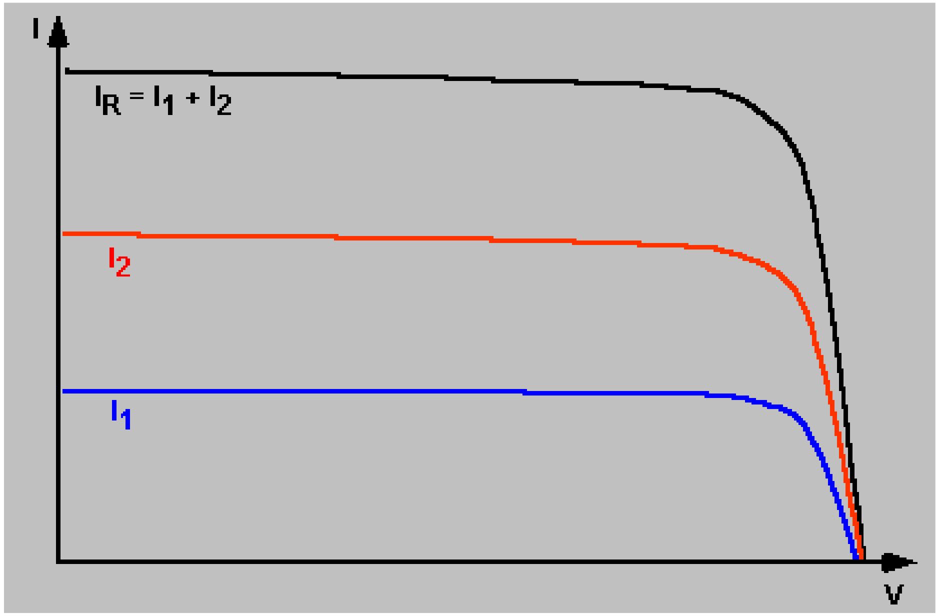
So in series connected solar cells and when the mismatch is in current then the current for the chain is set by the current of the worst performing cell,

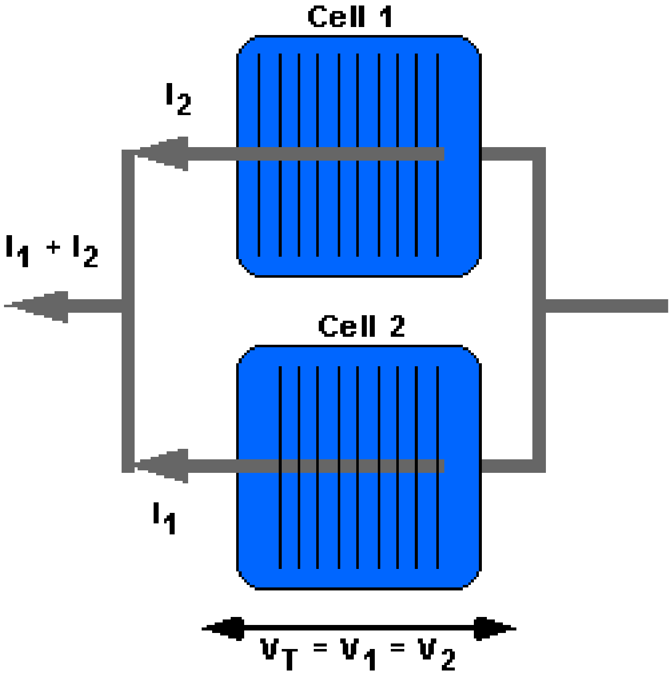


http://www.solar.udel.edu/ELEG620/13_PV_modules.pdf

Cells in parallel

Currents add, voltage is the same across cells in parallel.
Obviously can use parallel connection to boost current output.

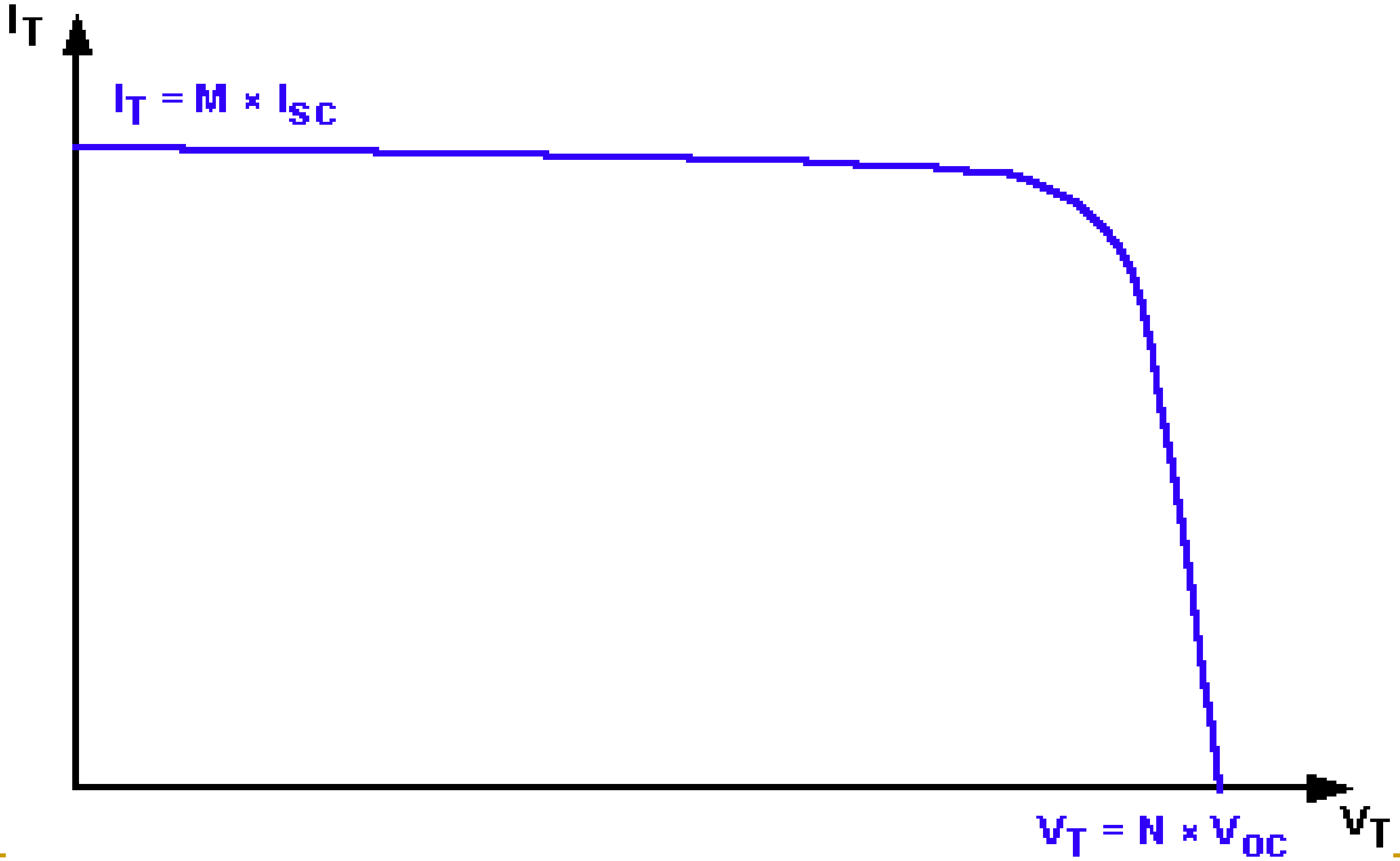




http://www.solar.udel.edu/ELEG620/13_PV_modules.pdf

I-V curve for N cells in series M cells in parallel

- Series connection increases voltage
- Parallel connection increases current

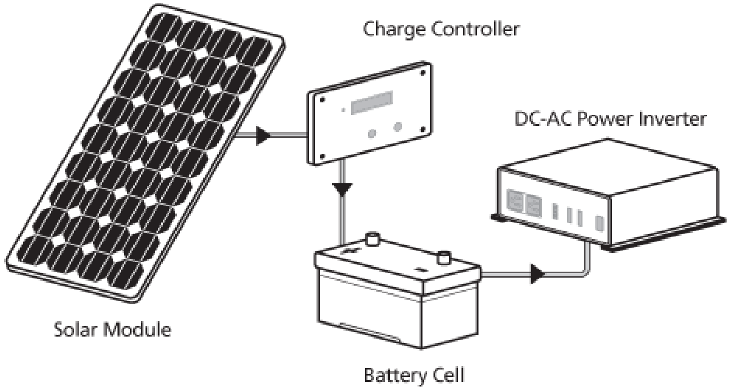


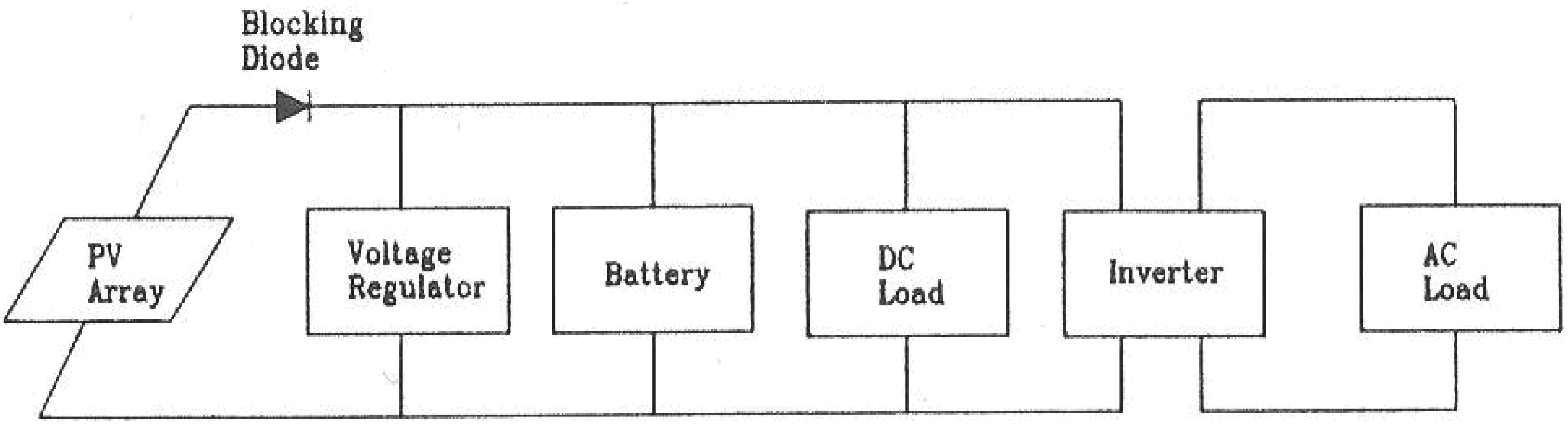
Example- array sizing

- An application requires 120 Watts at 12 volts, how many cells you will connect to form the array to meet the load given that Vmp= 0.50, MP = 1.0 W/cell.
- Cells in series to get 12 volts =12/0.5 = 24 cells.
- Current for application I = power /voltage = 120/12 = 10 ampers.
- Imp=1/0.5=2 ampers per cell
- To obtain 10 ampers need to connect cell in parallel = I total/I cell = 10/2 =5 in series.
- Your array consists of five strings in parallel each string contains 24 cells in series. Total number of cells = 5*24 = 120 cells

PV basic system

- The PV system contains the PV arrays, the batteries, battery regulator, inventor in addition to the load. As shown in figure below.





PV Subsystems – Inverters & Controllers

- Inverters

  Inverters are required to convert the power from the PV's from DC to AC. Recently produced inverters are reliable and efficient.
- Charge controllers

  Regulate the voltage entering batteries to avoid overcharging the batteries. Available in different capacities and must be selected to match the system. It prevents losses of power back through the panels at night.

Characteristics of a battery

- The key characteristics of a battery in a renewable energy system are:
  - efficiency of the battery;
  - how battery capacity and lifetime is affected by deep cycling and extended states of low charge;
  - the initial and ongoing battery costs; and
  - the maintenance requirements of the battery
- Batteries manufactured for other applications are not well suited to photovoltaic energy applications.
- Industrial Chloride batteries. These batteries are the best choice for PV systems as they can be discharged 80%. There are some larger capacity deep cycle batteries that will last 7-10 years.
- Nickel-cadmium batteries are costly but can last a very long time if they are not discharged excessively

Applications

- For areas where no grid supply since its cost cannot be compared to conventional electric generation systems. All applications of a photovoltaic generator must take into account its characteristic properties:

  a)The solar generator only supplies electricity when it is illuminated

  b)The amount of current generated depends on the radiation intensity.

  c)The solar generator supplies direct current

  d)It has a maximum power point determined by the current-voltage characteristic.

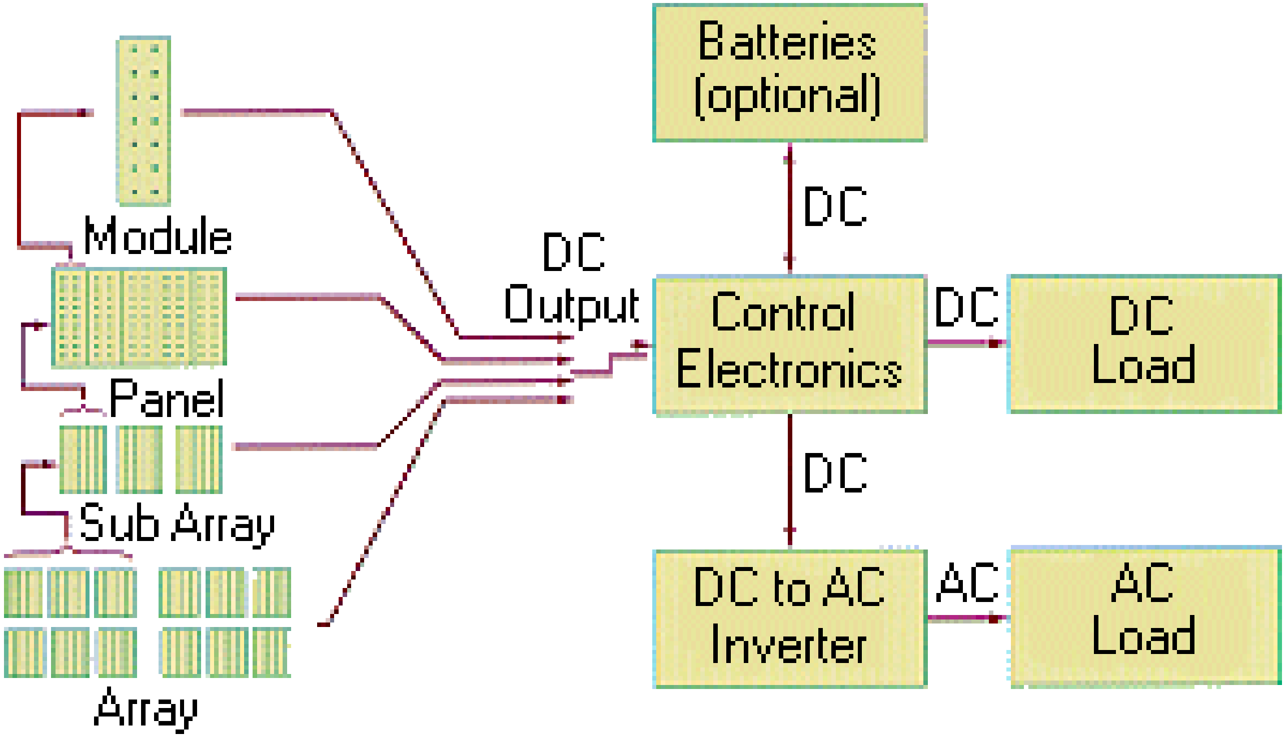
Applications

- The possible applications include:
    - Satellite and space crafts.
    - Telecommunication stations.
    - Remote localities with small loads.
    - Water pumping and vaccine refrigerators in rural areas

Stand-alone system

- Stand-alone system option requires batteries to store power for the times when the sun is not shining, since it does not use electric utility power.

Stand-alone system



A diagram of a typical standalone photovoltaic system

Grid-interface system

- Grid-interface system uses power from the central utility when needed and supplies surplus PV-generated power back to the utility.
- The interface between the PV produced- power can be metered in a manner that when power is produced by the PV's and sent into the grid the meter will run backwards. When power is brought in from the grid the meter will run in the regular direction

Hybrid systems

- Hybrid systems - those systems which use photovoltaic and some other form of energy, such as diesel generation or wind.

End of direct energy conversion