Direct Energy Conversion

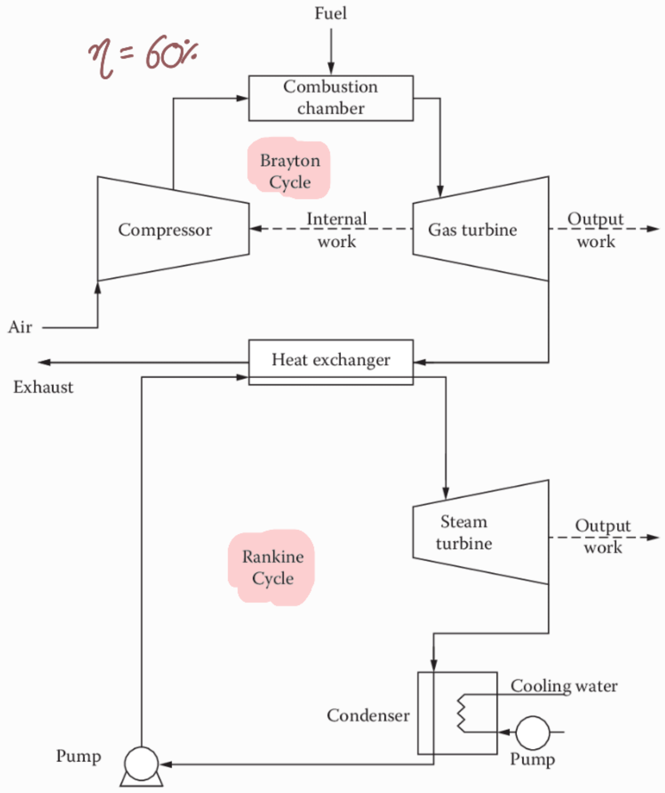
MHD Power	P 2-4
Thermoelectric Power	P 5-7
Thermionic Power	P 8-11
Photovolatic Power	P 12-15
Fuel Cells	P 16-21

check slides 25, 40, 43, 61, 62, 67, 70, 83, 138, 139

Topping and Bottoming

- Cycles are combined together to improve efficiency
- Topping cycles rejects its heat into a lower temp. steam cycle
- Combined cycles Power Plants are an example of that

$\eta = 60\%$



- These cycles uses less fuel per kwh & produce low emissions per kwh

Combined efficiency

$$\eta = \eta_p + (1-\eta_p)\eta_o$$

Topping unit efficiency

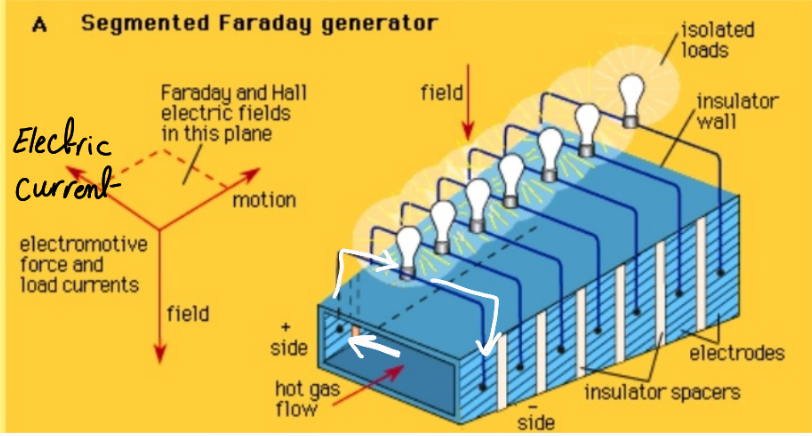
Conventional unit cycle

Magnetohydrodynamic Power

Thermal energy ⟶ Electrical energy

Working Principle

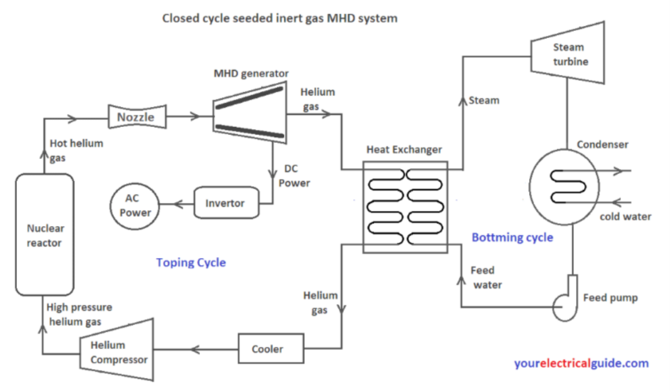
- Based on Faraday's law of electromagnetic induction
- Turbine and electric power generator are eliminated
- suited for large scale use since it depends on volume flow of gas
- Types of fluids used in MHD
  1. Ionized gas or plasma
  2. Liquid metal

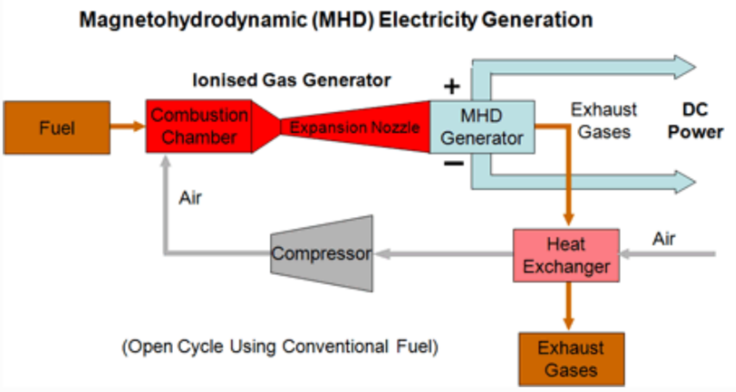


- Hot gas flows in the magnetic field, an electric field is created
- Channel walls are cooled to protect it from high Temperature
- Emf is induced in the gas and so an electric current goes through the external load, the gas and the electrodes

- Types of MHD cycles
  1 - Open Cycle
  2 - Closed Cycle

more efficient





Note:
The flowing current creates an induced field that interacts with the main field → Retarding Force

Hall effect

- It is caused by the axial Emf Resulting from Faraday interaction from the movement of electrical charges

Gas conductivity

- Highly dependant on temperature
- Enhanced by adding small quantities of seed
- Seed : easily ionized impurity such as K_2CO_3 or KOH (Pottasium) or cesium

Comparison between MHD & conventional Gas Turbine & Generator

MHD	Gas Turbine & Generator
operates at High Temperature 2000-3000°C	limited Temp since they have hot, highly stressed moving parts
Higher thermal efficiency than →	
No moving parts	loud, Viberating moving parts

Characteristics of the MHD

- Volume and length of the diverging flow channel
- $E_{ind} = C \times B$ V/m

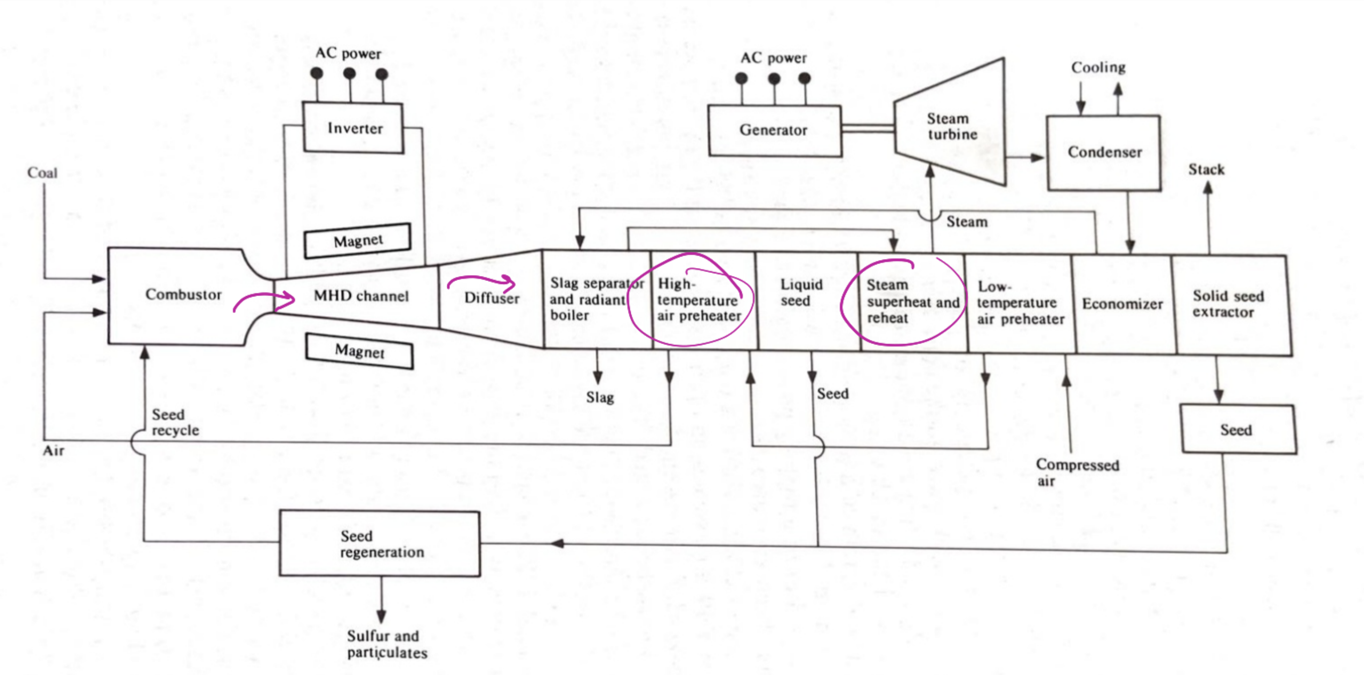
  Velocity of fluid conductor — Magnetic flux density

- $\eta = \frac{R_{ext}}{R_g + R_{ext}} = \frac{E}{E_{ind}}$
- $J = \sigma C B (1-\eta)$ A/m²
- $\dot{W} = VJA \rightarrow Ez$

  electrode area = xy

- $L = \frac{\boxed{P_1 - P_2}}{\sigma C B^2 (1-\eta)}$ → pressure drop

Magnetohydrodynamic Generator Analysis

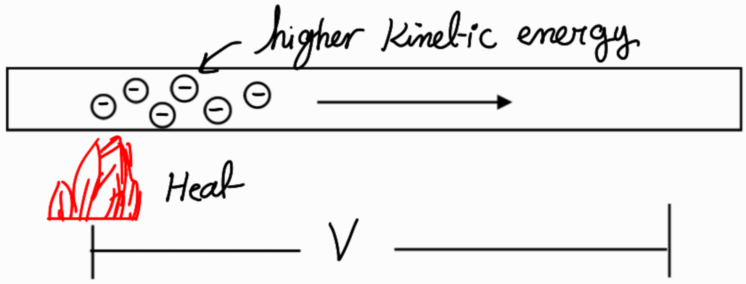


MHD Disadvantages

- Energy is required to energize magnets and air combustion

Thermoelectric Power

Thermoelectric effect



- Characterestics

1- The output voltage $\frac{1}{\propto}$ number of free electrons
2- Material conductivity $\propto$ number of free electrons

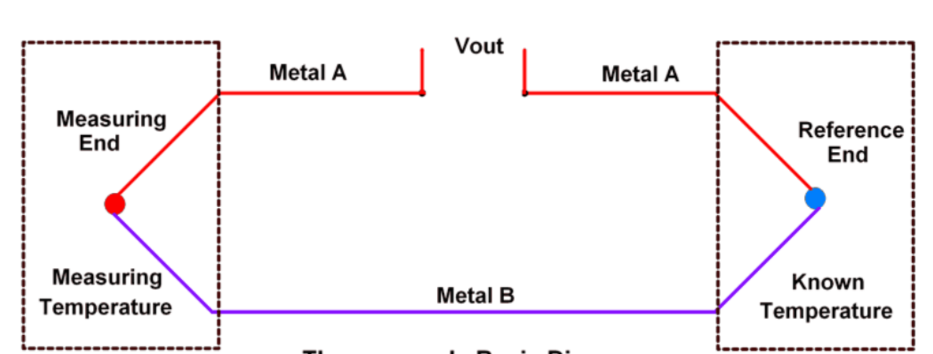
- Materials used

1- Insulators cannot be used :
It gives high voltage differenc but low current/Power since internal resistanc is high
They can be modified to acquire good thermo electric characteristics
Metallic additives are added to increase conductivity
2- Metals cannot be used :
It gives low voltage differenc but it has low internal resistanc
3- Semi Conductors are used. for example: lead Telluride (PbTe)

- Operating Temperature

when the Temp upper limit is reached, the material becomes
Intrinsic → No + or − charge carriers or equal number
Semiconductors become intrinsic at 1250K, insulators don't

Thermo Couple



Thermocouple Basic Diagram

- The reason for this limited application is the low energy conversion efficiency

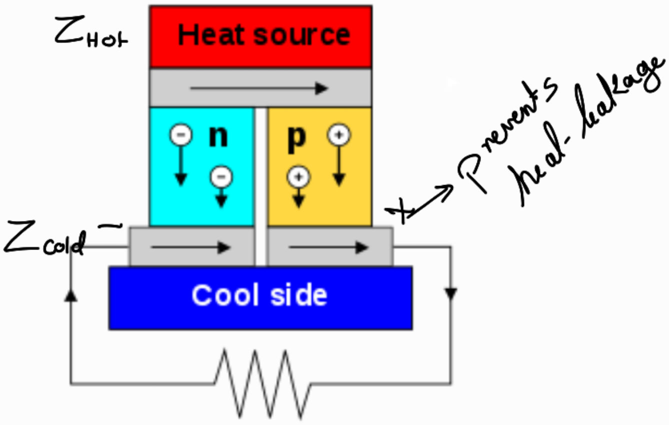
Basic Thermoelectric Generators

- Material

n-Type : has free electrons

p-Type : has holes

Heat → $\boxed{\text{TEG}}$ → Electrical energy



Preformance of thermoelectric Generator :

1- Seebeck coefficient

2- Electrical conductivity

3- Thermal conductivity

Figure of merit Z

$$Z = \frac{S^2 \sigma}{K}$$

$$M = Z\bar{T} \leftarrow \text{Average operating Temperature } \frac{T_h + T_c}{2}$$

Maximum conversion efficiency

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

$$\eta_c \to 1 - \frac{T_c}{T_h}$$

Note

If S, σ, K are given for n, p

$$Z = \frac{(S_1 + S_2)^2}{\left(\left(\frac{K_1}{\sigma_1}\right)^{1/2} + \left(\frac{K_2}{\sigma_2}\right)^{1/2}\right)^2}$$

S value is taken positive even if nigative

Maximum power

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

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

Area

material conductivity

Seebeck coefficient

Temperature Gradient

Element length

Burner efficiency

η_B = ratio of heat transferred through combustion chamber to the lower heating value of the fuel

$= 1 - 0.00045T$ ← stack gas Temperature in °C (High Temp)

Overall efficiency (Thermal efficiency)

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

Applications

- space vehicles
- Military equipement
- undersea installations

Thermionic emission

- Converts absorbed heat into electricity

Applications

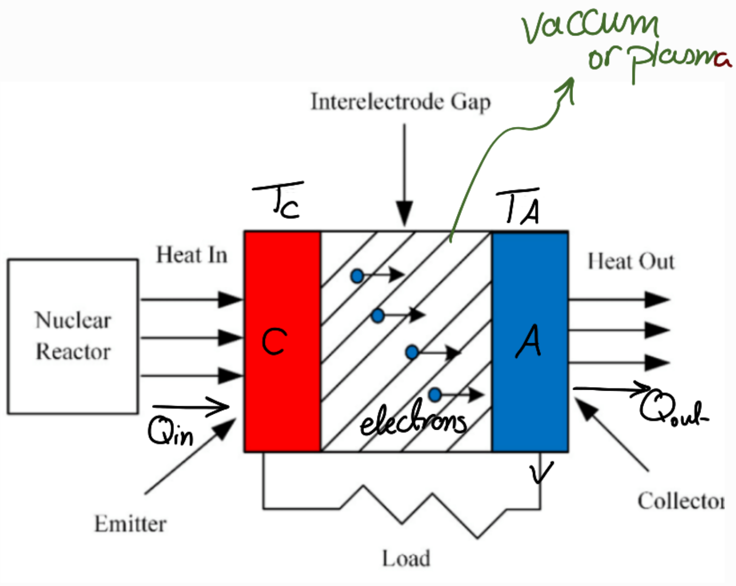
- Military and space applications

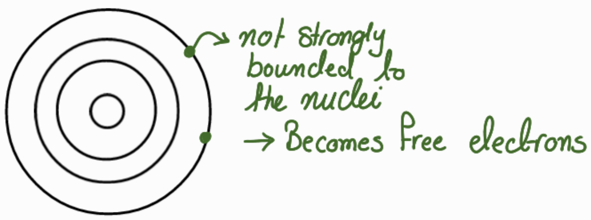
heat from Solar or Nuclear energy

fossil or nuclear fuel

Working principle

- Consists of two flat plates enclosed in a plasma or vacuum
- Cathode is made from a different material of anode
- $T_A < T_C$
- Free electrons exists in different energy levels



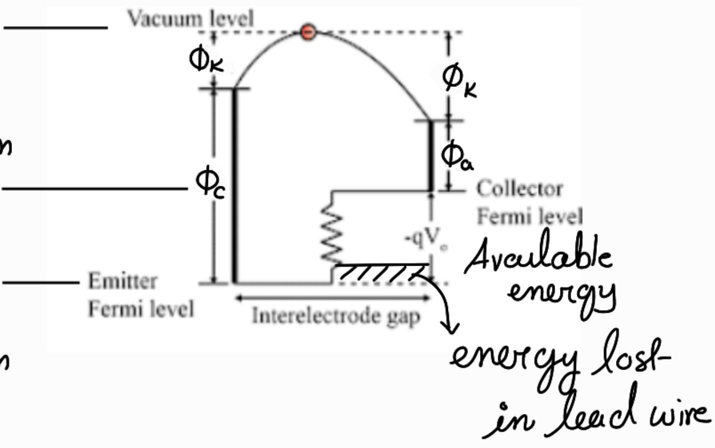


ϕ_c : Cathode work function

→ Energy required for the electron to escape the cathode

ϕ_a : Anode work function

→ Energy required for the electron to escape the anode



$\varnothing_k$: Kinetic energy of electrons needed to move through vacuum

$\varnothing_K + \varnothing_c$ = Gained energy from heat
$\varnothing_K + \varnothing_a$ = Energy lost from electrons striking the anode (Rejected as heat)
$\varnothing_c - \varnothing_a$ = Available energy

- To prevent space charge which prevents electrons flow from the cathode, a 0.01 mm interelectrode distanc is used

→ Types of such converters are:

1. Vacuum close spaced diodes
2. Plasma diodes which uses ionized gas on an interelectrode space. For example: Cesium Vapor, rubidium and pattasium

High pressure
low pressure

However: heat transfer increase between diods by convection

Preformanc

$$W_{out} = \varnothing_c - \varnothing_a - \varnothing_L$$

losses in the lead wire

Thermal efficiency

$$\eta_{Th} = \frac{J_{max}(V_c - V_a)}{J_{max}\left(V_c + 2\frac{K}{e}T_c\right) + \dot{Q}_r} = \frac{\dot{W}}{\dot{Q}_s}$$

output power

supplied power (Heat)

$$= \varnothing_c + 2KT_c + \dot{Q}_r$$

Saturation Current

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

Maximum electron current that an emitting surface can produce / Area

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

power

Radiation losses

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

$$F_e = \frac{1}{\frac{1}{e_c} + \frac{A_c}{A_a}\left(\frac{1}{e_a} - 1\right)}$$

, e_a, e_c emissivity values for the cathode and anode surfaces

Construction

Arrangements of thermionic Converters:

1. Two-spaced flat plates
2. Concentric cylinders (Used for nuclear thermionic converters)
   → inner cylinder as the emitter

Materials used:

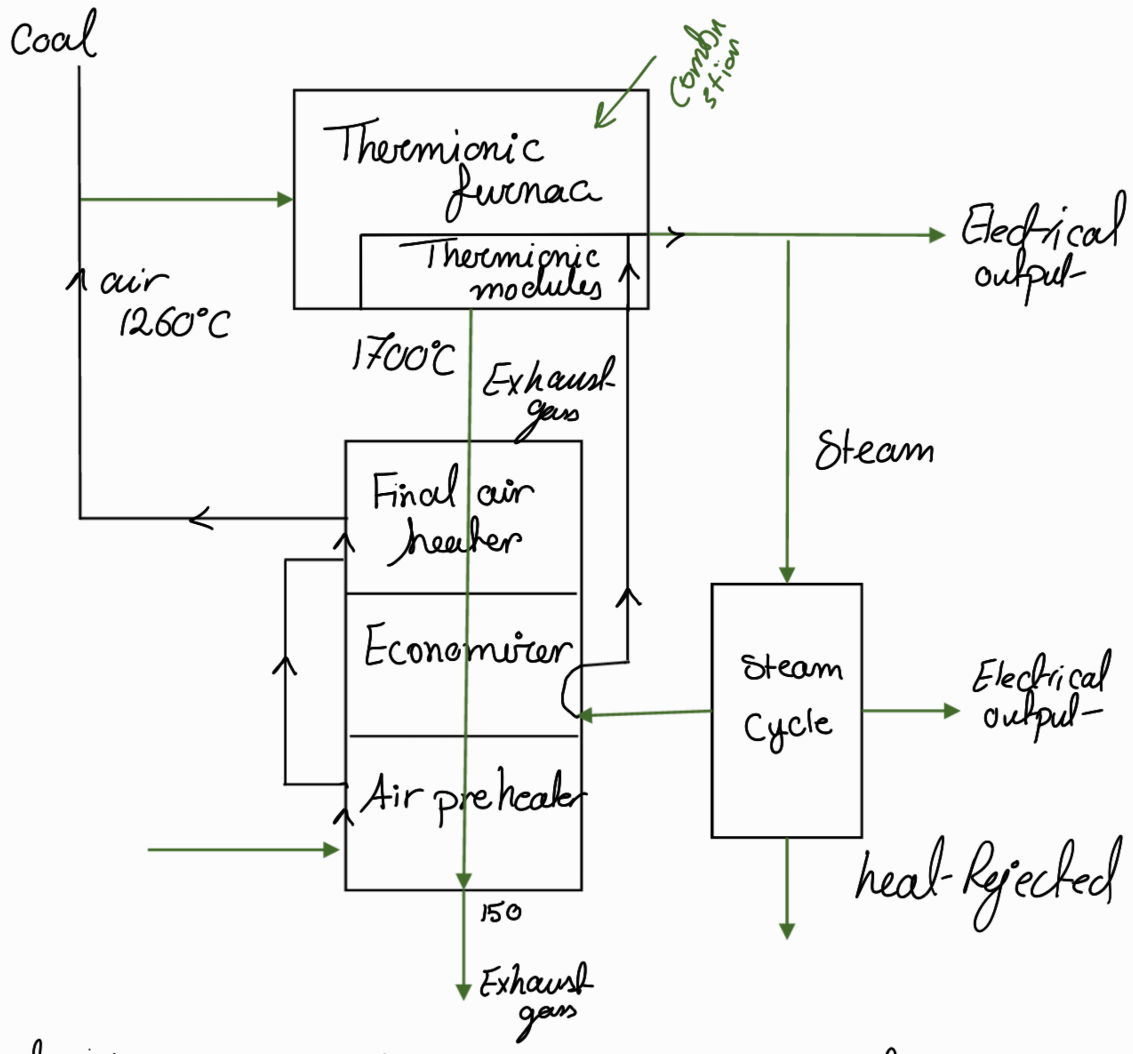
For Cathode

1. Tungsten
2. Barium oxide

For Anode

1. Silver Oxide
2. Tungsten Oxide
3. Copper

Thermionic Topping Powerplant



- Coal and hot air enters the thermionic furnanc which results in the combustion of the Coal
- Thermionic modules are heated with the heat rejected from the combustion.
- Resultant Exhaust gases passes through the final air heater, the economizer and the air preheater.
- Air pre heater is used to raise the temperature of the ambinet air which then passes to the final air heater which raises the temperature of the air again
- The economizer recieves steam from the steam cycle, heats i and then passes it to the thermionic moduls which heats i again.

Photovolatic Power

Solar Cells

- Converts solar energy into electrical energy
- Materials used : Silicon, germanium, cadium sufide & gallium arsenide
- $\frac{Power}{Mass} \uparrow$ as Solar cell Thickness $\downarrow$

- The negative surfac is placed facing the Sun for radiation resistanc
- Types of solar cells:
  1- Silicon cells
  2- Thin film
  3- Poly crystalline semiconductor

- Silicon cells are often used:
  1- They have superior conversion efficiency
  2- They have longer life

→ The conventional silicon cell is a n/p type semiconductor device

phosphorus ↗ ↖ Boron

The photovolatic effect

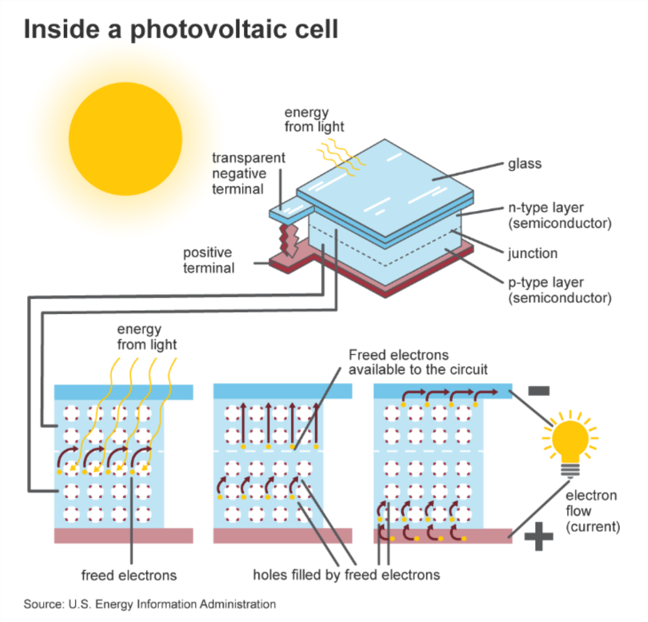
— P–n material

Doping

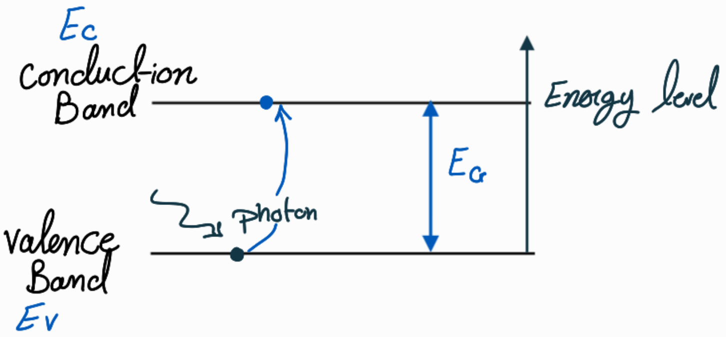
- n-Type Silicon: arsenic or phosphrus are added (Contains one more electron)
- P-Type Silicon: Boron or gallium are added (Contains one less electron)

Between them is the n/P Junction

- When solar photons hit the cell they are absorbed in the vicinty of the np Junction
- This will cause electrons to move to the conduction Band (Higher energy level due to the energy absorbed by photons)
- This will leave holes behind and so create a potential difference
- Free electrons will flow in the load circuit


Inside a photovoltaic cell

Source: U.S. Energy Information Administration



Solar Power generation

- Solar Cells are arranged in modules and modules are arranged in arrays (series or parallel)
- Solar constant: the unit intensity of solar radiation on a surface normal to the sun's ray.

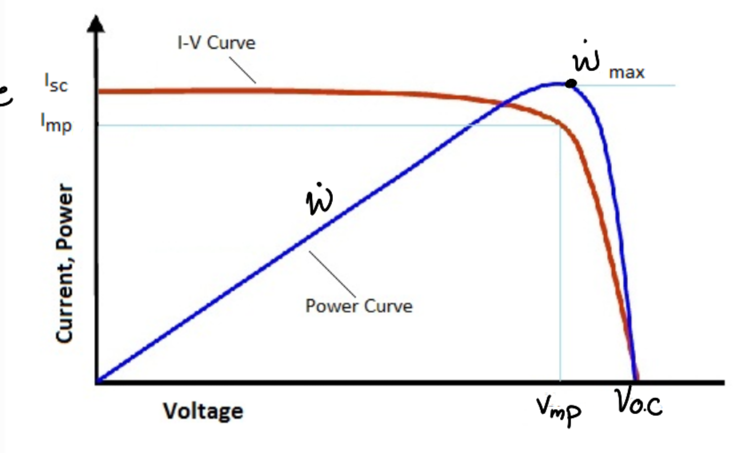
- To provide constant power output throughout the year, energy storage systems are used ⇒ Stand alone system

- Grid interface System: uses power from the central utility when needed & supplies surplus PV generated power back to the utility

I-V Curve for Solar cells

I_{sc}: current passing the cell when $V=0$

V_{oc}: maximum voltage available from a solar cell



Preformance

$$I_J = I_d\left(e^{\frac{eV}{KT}} - 1\right)$$

Junction current

Dark / Reverse current

$$I = I_{sc} - I_J$$

constant current at no load

Load current

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

Conversion efficiency

$$\eta_{max} = \frac{\dot{W}_{max}}{\dot{W}_{in}}$$

Solar Power input

usually $= \dot{E}(W/m^2) \times A(m^2)$

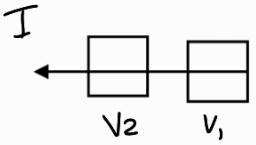
Max Power $= \dot{W}_{max} = \dfrac{V_{mp}(J_s + J_o)}{(KT/eV_{mp}) + 1}$

PV Testing and Rating

P_{rated} : Rated power of the solar cells at a radiation of 1 KW/m²
P_{actual} : Actual power delievered by the solar cell at non-standard radiation

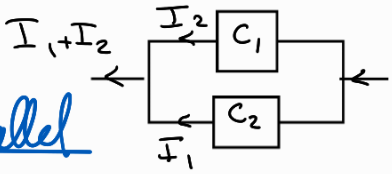
$$P_{actual} = \underset{\text{Pat 1 KW/m}^2}{P_{rated}} \times \underset{\text{KW/m}^2}{E_{solar}}$$

Solar cells arrangement



Series

- Same Current
- Voltage adds up



Parallel

- Same Voltage $\vdash$ V $\dashv$
- Current adds up

PV Basic System

- Contains :

1- PV arrays
2- Voltage Regulator
3- Battery : Industrial chloride batteries are the best choice
4- Inverter : Converts power from DC to AC
5- Load
→ Subsystems : Inverters & Charge Controllers

Regulates voltage entering Batteries to avoid over-charging

Applications

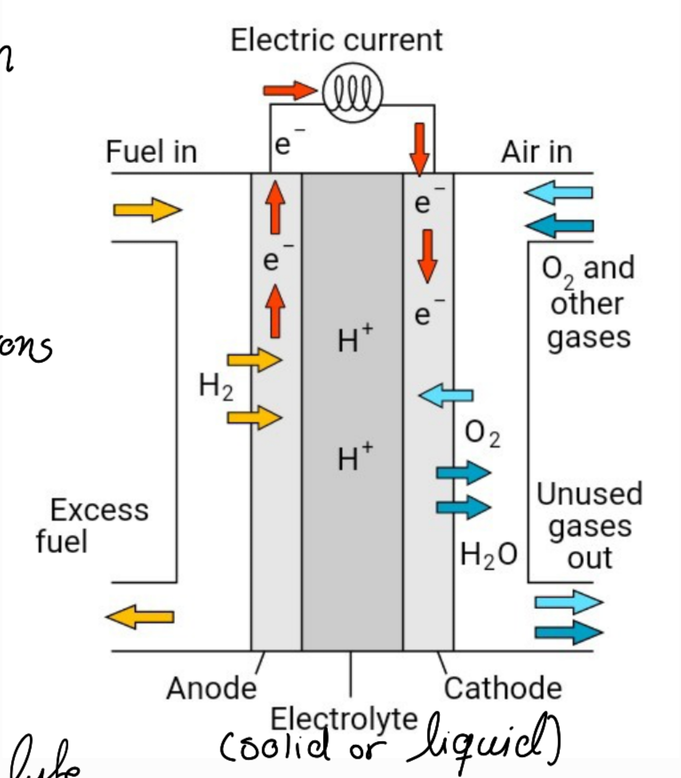
1- Satellite and space crafts
2- Telecommunication stations
3- Remote localities with small loads
4- Water pumping & vaccine refrigerators in rural areas

Fuel Cells

- Converts chemical energy into electric energy
- operating temperature can reach 600 to 650°C where molten salt electrolyte system is used / η_{Th} is not limited by 2nd law

Working Principle

-Typical Hydrogen/oxygen fuell cell



- on the anode surfac, the hydrogen reacts with the electrolyte to produce electrons and ions

$$2H_2 \longrightarrow 4H^+ + 4e^-$$

- Electrons travel through the external circuit, then back to the cathode
- Ions move from the electrolyte to the cathode, then, they combine with the e^- & O_2 forming H_2O

$$4H^+ + 4e^- + O_2 \longrightarrow 2H_2O$$

- Hydrocarbon fuels are used to provide hydrogen by the introduction of preliminary reaction (hydrocarbon becomes more reactive in a steam re-former)

Hydrocarbon + Steam → $H_2 + CO_2$

→ Hydrocarbons can react immediately with oxygen by: Improving the electrode structure and using liquid electrolyte (phosphoric acid)

- Reactions in Methane / air fuel cell

Anode: $CH_4 + 2H_2O \longrightarrow CO_2 + 8H^+ + 8e^-$

Cathode: $8H^+ + 8e^- + O_2 \longrightarrow 4H_2O$

Materials used

Electrodes

- Cheracteristics: Porosity, Catalyst, Electrical conductivity and Resistanc to Corrosion
- Anode → platinum
  Cathode → palladuim

Electrolyte

Types of fuel cells based on the electrolyte:

1- Aqueous: $T_{range} = 0 - 200°C$

- Alkaline Electrolyte

from electrolyte (solution)

Cathode $O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$

Anode $2H_2 + 4OH^- \longrightarrow 4H_2O + 4e^-$

- Acid Electrolyte

Anode $2H_2 \longrightarrow 4e^- + 4H^+$

Cathode $4H^+ + 4e^- + O_2 \longrightarrow 2H_2O$

* Proton exchange membrane fuel cell

Electrolyte: water based acidic polymer membrane

Electrodes: platinum based

$T_{operation}$: low Temp. (< 100°C)

- operates on pure hydrogen
- Same work principle as conventional fuel cell / H_2O as a result

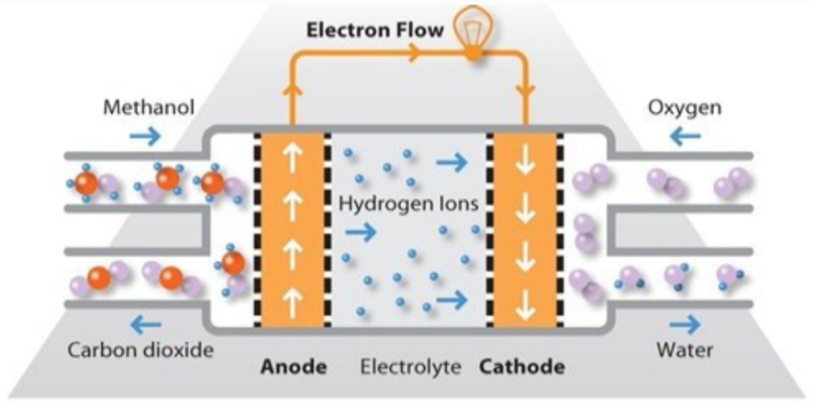
* Direct methanol fuel cell

Electrolyte: polymer membrane

Electrodes → Anode: platinum ruthenium catalyst (Draws hydrogen from liquid methanol → No need for fuel reformer / CO_2 & H_2O results

T operation: 60° – 130°C

- used for modest power requirements such as mobile electronic devices & chargers + forklifts of warehouses

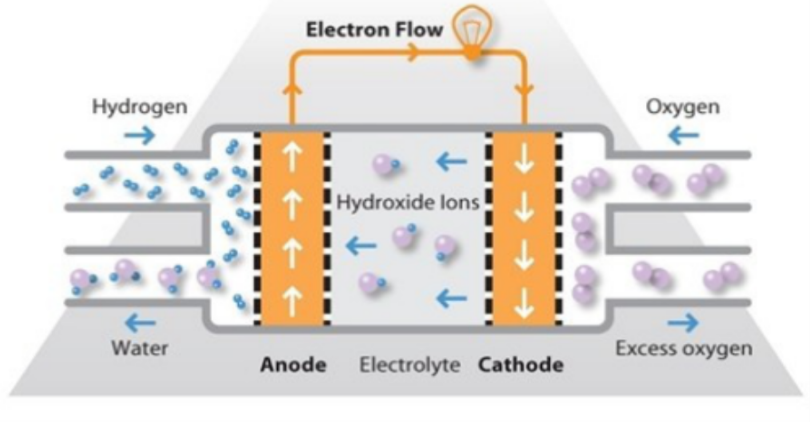


* Alkaline fuel cells

Electrolyte: Alkaline electrolyte such as pottasium hydroxide in water

T operation: 70°C so no need for platinum catalyst

- operates on pure hydrogen / H_2O & O_2 results
- used in space by NASA to produce H_2O & electricity



2- Molten Salt : $T_{range} = 500\text{-}700°C$

Example: molten Carbonates

Anode $H_2 + CO_3^{-2} \longrightarrow H_2O + CO_2 + 2e^-$

cathode $\frac{1}{2}O_2 + CO_2 + 2e^- \longrightarrow CO_3^{-2}$

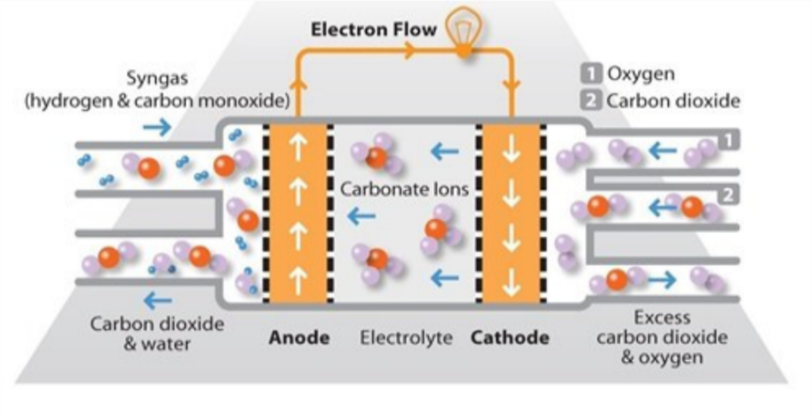
* Molten carbonate fuel cells

Electrolyte: Molten Carbonate salt suspended in a porous Ceramic matrix / Salts used: lithium carbonate, Pottasium Carbonate & sodium carbonate

$T_{operation}$: High Temp. (650°C) / no need for noble metal Catalyst to Boost Reaction → T_{High} so better reaction Kinetics

Reactions: Anode: $H_2 + CO_3^{-2} \longrightarrow H_2O + CO_2 + 2e^-$

Cathode: $\frac{1}{2}O_2 + CO_2 + 2e^- \longrightarrow CO_3^{-2}$



3- Solid Electrolyte : $T_{range} = 700°C$

Contains $\underbrace{\text{ion species}}_{\substack{85\%\ ZrO_2 \\ 15\%\ CaO}}$ which Becomes mobile at T_{High}

Anode $H_2 + O^{-2} \longrightarrow H_2O + 2e^-$

Cathode $\frac{1}{2}O_2 + 2e^- \longrightarrow O^{-2}$

* Solide oxide fuel cells

Electrolyte: Solid ceramic such as: zirconium oxide stabilized with yttrium oxide instead of liquid or membrane

$T_{operation}$: High Temp. (800°C to 1000°C)

- High efficiency 60%

Preformance

Theoretical

- Reversible & Isothermal

$$W_{rev} = \Delta G = \Delta H - T\Delta S \Rightarrow \text{Values from Table 12.2}$$

Rejected heat

increases as the operating T increases

Conversion efficiency

$$\varepsilon_i = \frac{\Delta G}{\Delta H}$$

$\varepsilon_i \downarrow$ as $T_{operating} \uparrow$

Electrical energy

$$\Delta G = -E_{rev} I \tau$$

Time for consuming one mole of fuel

Cell emf

$$= -\underbrace{z F^{\circ}}_{\text{Transferred charge}} E_{rev}$$

Electro chemical valenc

constant

$\Rightarrow$ Values for z & E_{rev} from Table 12.3

Actual

- Irreversible

$E_a < E_{rev} \Rightarrow W_a < W_{rev}$

Because of:

- unwanted reactions in the cell
- impedement to reaction at the anode or the cathode
- I^2R heating in the electrolyte

$$-E_a I \tau = \Delta H - Q$$

→ in KJ/Kgmol

To calculate in KJ/hors

$$\dot{Q} = \frac{Q}{\tau\,(\text{hors})}$$

Conversion Efficiency

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

→ in s

in J/Kgmol

Applications

- Space Applications
- Utility Companies → No pollution, no sitting problems and location flexibility
- Automotive vehicles : hybrid applications
- Aerospac applications
- laptop & mobile applications