Power Plant Engineering

Prepared By :
Dr. Naruttam Kumar Roy
Professor
Dept of EEE, KUET

Edited By :
Dr. Golam Saleh Ahmed Salem
Dept of EEE, UGV

Department of Electrical and Electronic Engineering
University of Global Village

Course Contents

- **Typical layout of a substation and load curves: Demand factor, diversity factor, load duration curves, energy load curve, load factor, capacity factor, plant use factor and load forecasting.**
- **Planning of power plant: Types of power plants, generating capacity and selection of plants, types of load and their effects, site selection for different plants.**
- **Station performance: Efficiency, depreciation of plant, heat rate and incremental rate, load division between generating units for economy, cost and tariff. Generation scheduling: deterministic and probabilistic.**

Course Contents…

- **Conventional power plant:** **Hydro and thermal power plant, generating cost.**
- **Nuclear power plant:** **Nuclear fission and fusion; energy release; moderation, control, cooling and shielding aspects; types of nuclear reactor; safety measures for nuclear power plants.**
- **Non-conventional power generation:** **Photovoltaic (PV) power generation: principle and applications, maximum power point operation, standalone PV system, grid-connected PV system, concentrated PV system; wind: principle and applications, wind energy system components, classification of wind electric system, performance of wind machines; fuel cell; tidal, bio-gas and bio-mass, geothermal, thermo-electric, thermionic and magneto hydrodynamic power generation; variation in availability of renewable energy sources; storage of electricity.**
- **Reliability concepts: Failure rate, outage, mean time of failure, series and parallel systems and redundancy, reliability evaluation techniques.**

Intended Learning Outcomes (ILOs)

Upon completion of this course students should be able to

- **explain the configuration of substation, load curves, load forecasting techniques and tariff.**
- **plan power plants and recommend site for different types of plants.**
- **investigate economic operation of plants and assess station performance.**
- **illustrate the construction and operation of conventional and non-conventional power plants.**
- **describe reliability concepts and their evaluation techniques in the power station.**

Assessment Components

Assessment item 1: **Attendance**
Assessment item 2: **Class Test**
Assessment item 3: **Final Examination**

Learning Resources

- Power Plant Engineering by Black & Veatch, Lawrence F. Drbal (auth.), Lawrence F. Drbal, Patricia G. Boston, Kayla L. Westra (eds.)
- Power Plant Engineering by P. K. Nag
- An Introduction to Nuclear Power Generation by Christopher E. Brennen
- Power Plant Engineering by G. R. Nagpal
- T. Ackermann, Wind Power in Power Systems, John Wiley & Sons
- Principles of Power System by V. K. Mehta
- Elements of Electrical Power Station Design by M. V. Deshpande
- Renewable Energy and the Environment by M.R. Islam, N.K. Roy, S. Rahman (eds.)
- Lecture notes

Electrical Energy

Energy is the basic necessity for the economic development of a country.

Energy ⟶ the capacity of physical system to do work

The availability of huge amount of energy in the modern times has resulted in a shorter working day, higher agricultural and industrial production, a healthier and more balanced diet and better transportation facilities.

As a matter of fact, there is a close relationship between the energy used per person and his standard of living. The greater the per capita consumption of energy in a country, the higher is the standard of living of its people.

The conversion of energy available in different forms in nature into electrical energy is known as the generation of electrical energy.

Importance of Electrical Energy

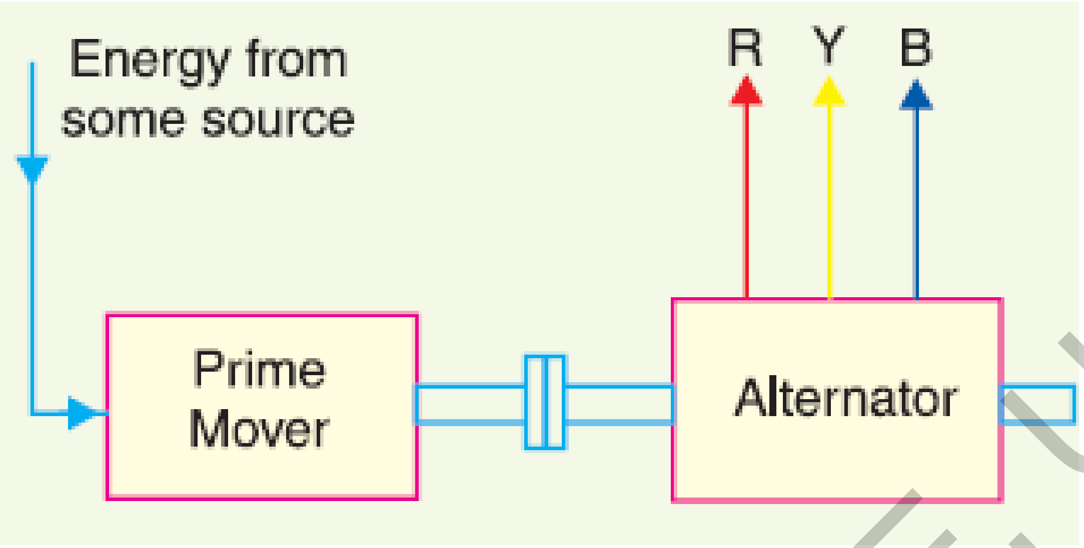
- ✓ **Convenient form**
- ✓ **Easy control**
- ✓ **Greater flexibility**
- ✓ **Cheapness**
- ✓ **Cleanliness**
- ✓ **High transmission efficiency**

Generation of Electrical Energy

Energy is available in various forms from different natural sources such as pressure head of water, chemical energy of fuels, nuclear energy of radioactive substances etc.

All these forms of energy can be converted into electrical energy by the use of suitable arrangements.

Generation of Electrical Energy (contd.)



Sources of Energy:

- **Sun**
- **Wind**
- **Water**
- **Fuels**
- **Nuclear energy**

The prime mover is driven by the energy obtained from various sources such as burning of fuel, pressure of water, force of wind etc. For example, chemical energy of a fuel (e.g., coal) can be used to produce steam at high temperature and pressure. The steam is fed to a prime mover which may be a steam engine or a steam turbine. The turbine converts heat energy of steam into mechanical energy which is further converted into electrical energy by the alternator.

Similarly, other forms of energy can be converted into electrical energy by employing suitable machinery and equipment.

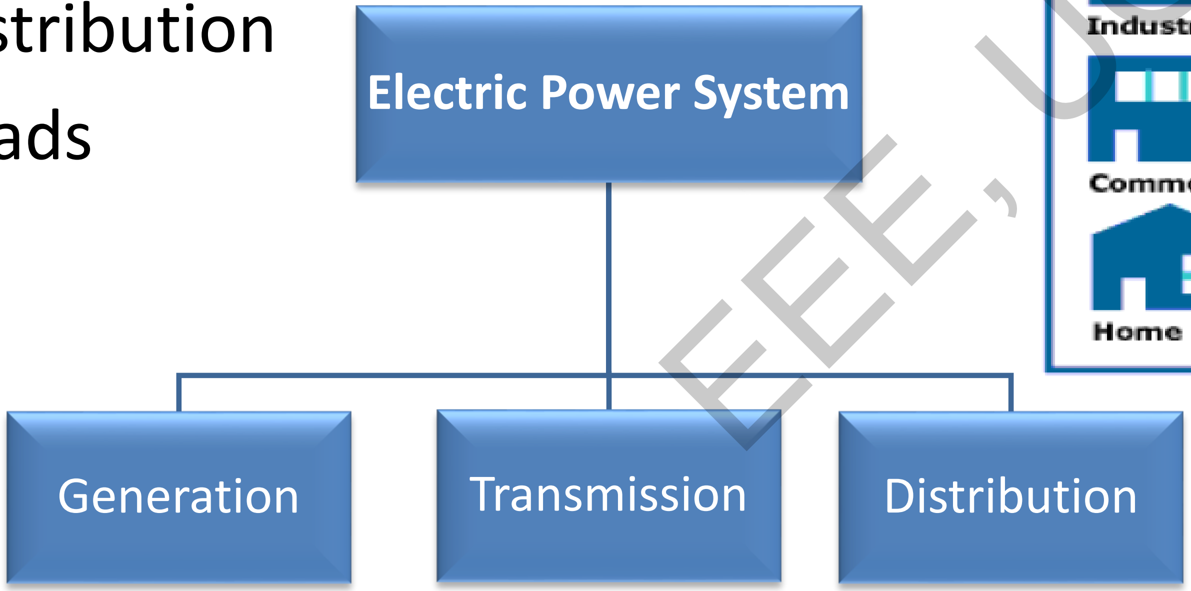
Comparison of Energy Sources

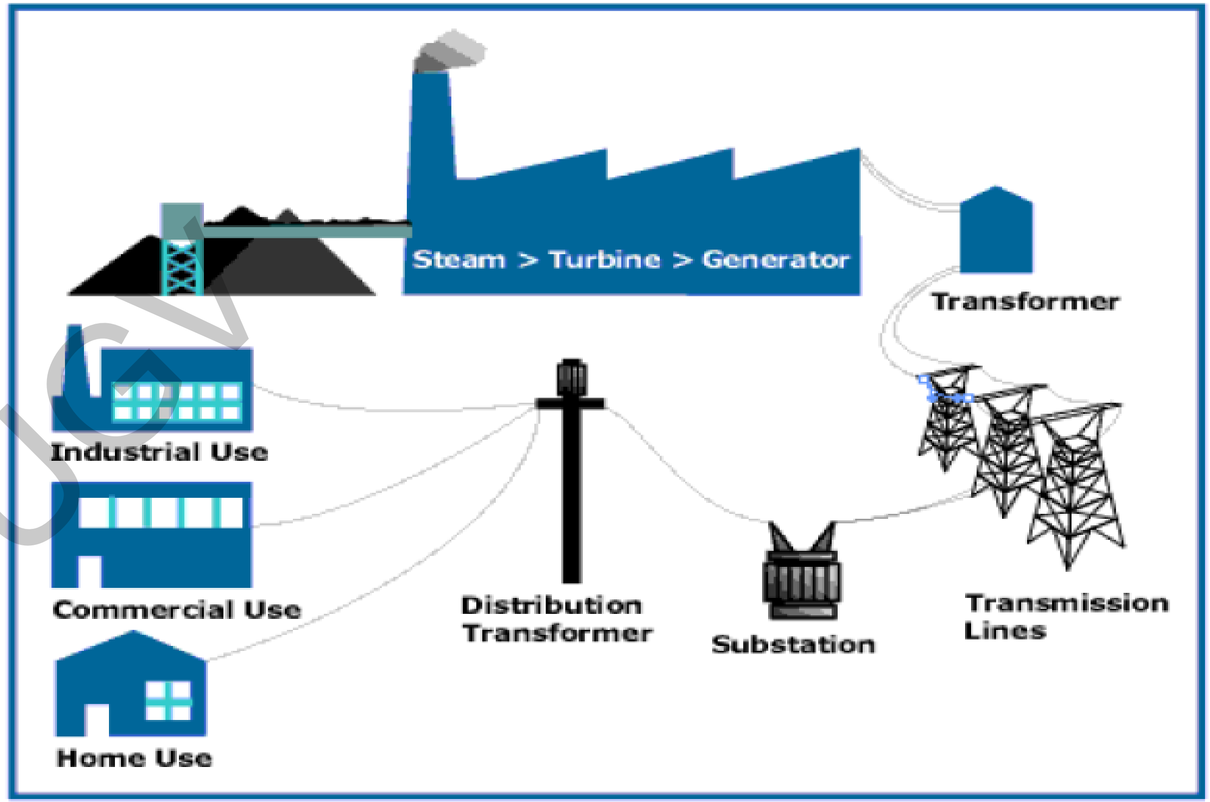
S.No.	Particular	Water-power	Fuels	Nuclear energy
1.	*Initial cost*	High	Low	Highest
2.	*Running cost*	Less	High	Least
3.	*Reserves*	Permanent	Exhaustable	Inexhaustible
4.	*Cleanliness*	Cleanest	Dirtiest	Clean
5.	*Simplicity*	Simplest	Complex	Most complex
6.	*Reliability*	Most reliable	Less reliable	More reliable

Fundamentals of Electric Power Systems

Major parts of power system

- Generation
- Transmission
- Distribution
- Loads





Basic components of a power system

Power System is an integrated network that interconnects the installations for generation, transmission and distribution of electricity.

Nuclear power plant

Definition

The generating station in which **nuclear energy is converted into electrical energy** is known as a nuclear power station.

The energy released by burning one kilogram of uranium is equivalent to the energy obtained by burning 4500 tones of high grade coal.

1 kg Uranium ≈ 4500 tones of coal

Why Nuclear?

Conventional thermal power stations use **oil or coal as the source of energy**.

The reserves of these fuels are **becoming depleted in many countries**, and thus there is a tendency to seek alternative sources of energy.

Advantages

- It reduces the demand for **coal, oil and gas,** the costs of which are tending to rise as the stocks become depleted.

- The transport of conventional fuel to the station involves **cost as well as delay** if the transport facilities are not available in time. The **weight of the nuclear fuel** required for a station of the same capacity is almost negligible in comparison and problems of transport do not arise.

- Besides producing large amounts of power, the nuclear power plant can produce valuable **fissile material**, which is extracted when the fuel has to be renewed.

Advantages (contd.)

- The nuclear power station needs **less area and volume** compared to a conventional plant of equal capacity.

- Nuclear power plant is **partially independent of geographical factors,** the only requirement is good supply of water.

- Large quantity of energy is released with the consumption of only **a small amount of fuel**. So, the cost per kWh is less.

- It is a **clean source of energy** which does not pollute the air if radio-active hazards are effectively prevented.

Disadvantages

➢The capital cost of a nuclear power plant is **very high** as compared to other types of plants.

➢The erection and commissioning of plant requires **greater technical knowledge**.

➢The fission by-products are generally **radioactive** and may cause a dangerous amount of **radioactive pollution**.

Disadvantages (contd.)

➢ Maintenance charges are high due to **the lack of standardization**. Moreover, **high salaries of specially trained personnel** employed to handle the plant further raise the cost.

➢ They are not suitable for **variable load operation** as the reactors cannot be easily controlled to respond quickly to load changes. They are used at load factor of **not less than 80%.**

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

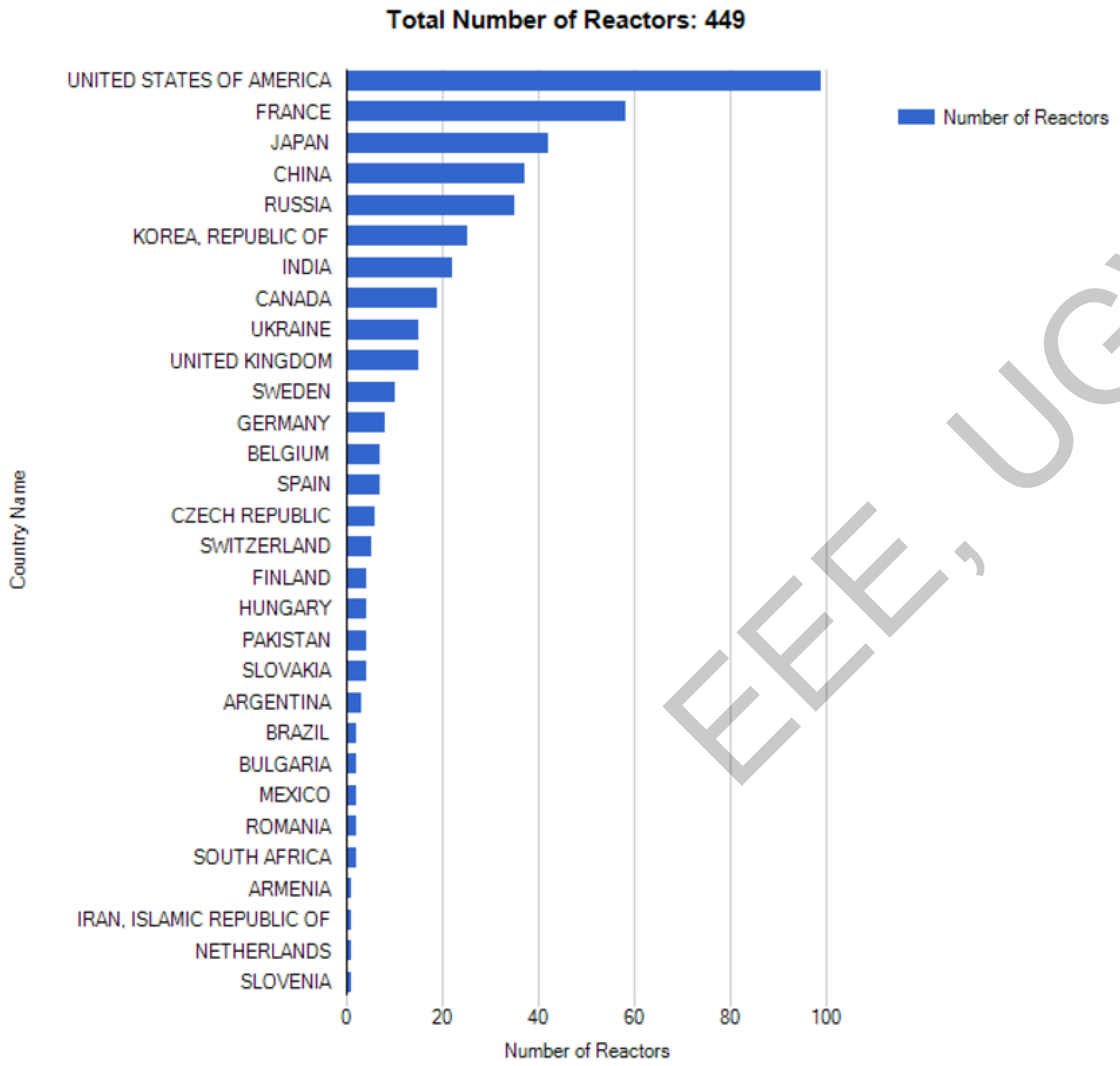
➢ The **disposal** of the by-products, which are radioactive, is a big problem. They have either to be disposed off in a **deep trench or in a sea away from sea-shore.**

Practical Applications

- **Bangladesh (under construction)**

  --- Rooppur Nuclear Power Plant

OPERATIONAL REACTORS



Country	Number of Reactors	Total Net Electrical Capacity [MW]
ARGENTINA	3	1632
ARMENIA	1	375
BELGIUM	7	5913
BRAZIL	2	1884
BULGARIA	2	1926
CANADA	19	13554
CHINA	37	32402
CZECH REPUBLIC	6	3930
FINLAND	4	2764
FRANCE	58	63130
GERMANY	8	10799
HUNGARY	4	1889
INDIA	22	6225
IRAN, ISLAMIC REPUBLIC OF	1	915
JAPAN	42	39752
KOREA, REPUBLIC OF	25	23077
MEXICO	2	1552
NETHERLANDS	1	482
PAKISTAN	4	1005
ROMANIA	2	1300
RUSSIA	35	26172
SLOVAKIA	4	1814
SLOVENIA	1	688
SOUTH AFRICA	2	1860
SPAIN	7	7121
SWEDEN	10	9740
SWITZERLAND	5	3333
UKRAINE	15	13107
UNITED KINGDOM	15	8918
UNITED STATES OF AMERICA	99	99869
Total	**449**	**392180**

Source: http://www.rooppurnpp.gov.bd/site/page/6e08482c-beb0-4ebb-a431-8984e0b56063/-

Principle of Nuclear Energy

To appreciate the principle of nuclear energy and to understand how the nuclear reaction starts which produces heat, it is necessary for us to study a few basic principles of atomic physics.

This involves

- structure of atom
- binding energy of their nuclei
- interchanging of mass and energy
- how a chain reaction starts and
- emission of certain particles which produce radiation hazards

Structure of atom

All matters are composed of unit particles called atoms.

Atom → The smallest particle into which an element can be divided

An atom consists of a relatively heavy, positively charged nucleus and a number of much lighter negatively charged, electrons orbiting around the nucleus.

Nucleus → **Proton + Neutron** } **Nucleons**

Structure of atom (contd.)

Atomic number (Z) → Number of protons

Mass number (A) → Number of nucleons

$$_ZX^A \quad or \quad ^A_ZX$$

X → Usual chemical symbol

^1_1H	^4_2He	^7_3Li
Hydrogen	Helium	Lithium

Summary

- **Course outlines & assessment procedure**
- **Importance of electrical energy**
- **Principal sources of generation of electrical energy**
- **Advantages & disadvantages of nuclear power plant**
- **Structure of atom**

Next class

- ❖ **Binding energy**
- ❖ **Nuclear stability**

Structure of atom

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Structure of atom (contd.)

Atomic number (Z) → Number of protons

Mass number (A) → Number of nucleons

$$_{Z}X^{A} \quad or \quad {}^{A}_{Z}X$$

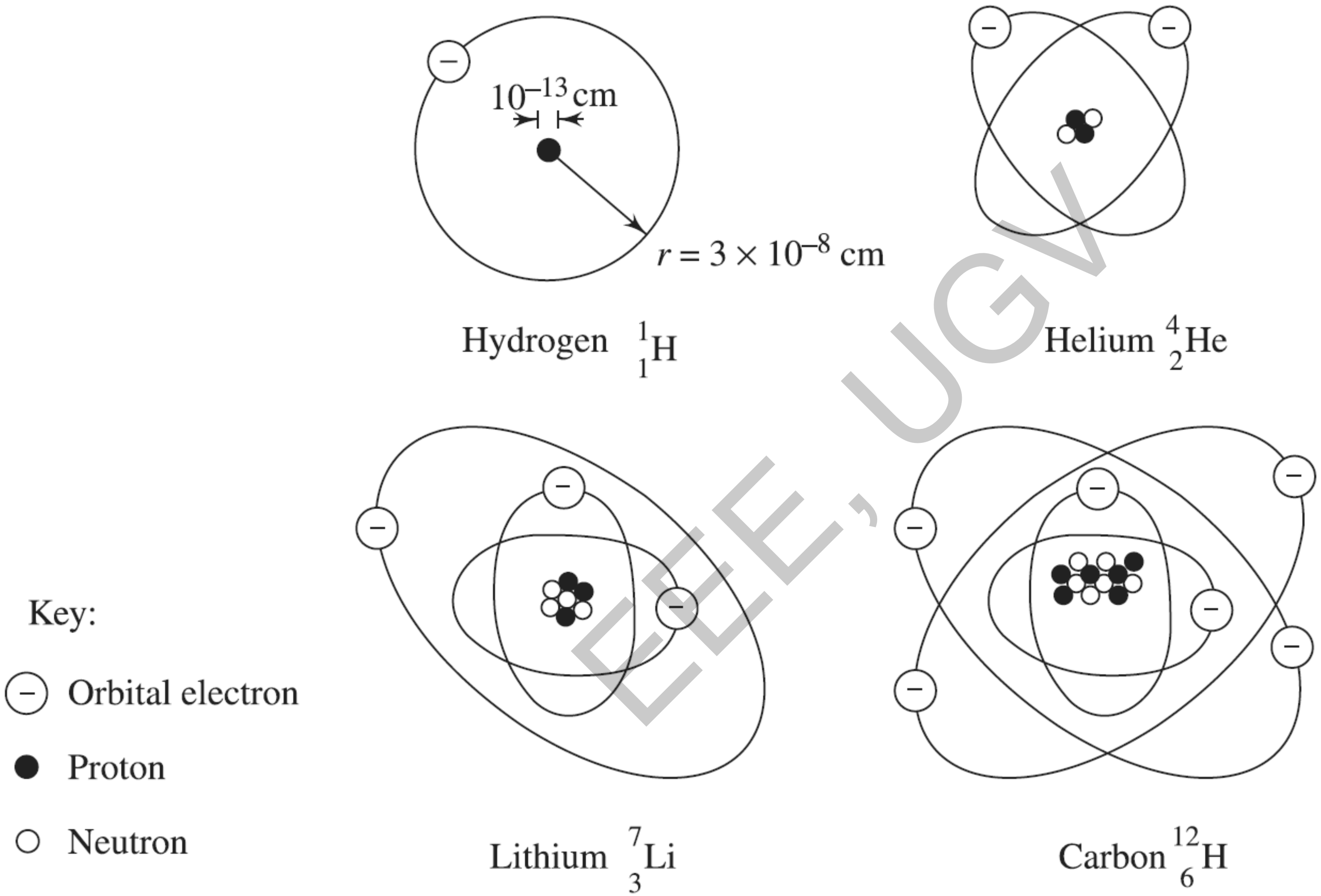
X → Usual chemical symbol

${}^{1}_{1}H$ Hydrogen

${}^{4}_{2}He$ Helium

${}^{7}_{3}Li$ Lithium

Structure of atom (contd.)



Electrons that orbit in the outermost shell of an atom are called **valence electrons** which decide the chemical properties of an element.

Structure of atom (contd.)

$$\text{Neutron mass, } m_n = 1.008665 \text{ amu} = 1.674 \times 10^{-27} \text{ kg}$$

$$\text{Proton mass, } m_p = 1.007277 \text{ amu} = 1.673 \times 10^{-27} \text{ kg}$$

$$\text{Electron mass, } m_e = 0.0005486 \text{ amu} = 9.109 \times 10^{-31} \text{ kg}$$

1 amu=1.66×10^{-27} kg

Structure of atom (contd.)

Isotopes:

Atoms with nuclei having the same number of protons have similar chemical and physical properties and differ mainly in their masses.

Example:

$$^{1}_{1}H, \quad ^{2}_{1}D$$

$$^{238}_{92}U, ^{235}_{92}U, ^{234}_{92}U$$

Isotope	Protons	Neutrons	Atomic mass
U-234	92	142	234
U-235	92	143	235
U-238	92	146	238

Natural Uranium → $^{238}_{92}U(99.282\%) + ^{235}_{92}U(0.712\%) + ^{234}_{92}U$ (0.006%)

Structure of atom (contd.)

- Isobars

The atoms which have the same mass number but different atomic numbers are called isobars.

$$^{40}_{18}Ar, ^{40}_{19}K, ^{40}_{20}Ca$$

$$^{235}_{92}U, ^{235}_{93}Np, ^{235}_{94}Pu$$

- Isotones

Atoms which have different atomic numbers and different atomic masses but the same number of neutrons are called isotones.

$$^{15}_{7}N, ^{16}_{8}O$$

Emission of particles

- Positron:

The positron is a positively charged electron having the symbols

$$_{+1}e^{0},\ e^{+} \text{ or } \beta^{+}.$$

The symbol for electron

$$_{-1}e^{0},\ e^{-} \text{ or } \beta^{-}$$

- Neutrino ($\boldsymbol{\vartheta}$):

The neutrino is a tiny, electrically neutral particle, ejected along with $\boldsymbol{\beta}$ particle during nuclear fission.

Emission of particles…

- Radio-active decay:

Some of the isotopes of some elements are **unstable and change or disintegrate spontaneously**. They are called radio-active isotopes and the phenomenon is called radio-active decay.

Some of the radioactive elements are **radium, thorium and uranium**.

The resulting nucleus is called the **daughter** and the original nucleus is called the **parent**. The daughter product may be stable or radio-active.

Emission of particles...

- **Alpha particles:**

Alpha particles or nuclei of helium-4 (α or ${}^{4}_{2}He$) are emitted from the nuclei of radio-active isotopes at a high velocity of about $3 \times 10^9\ cm/sec$ or $\frac{1}{10}$ of the speed of light and carry a positive charge.

$$ {}^{239}_{94}Pu \xrightarrow{\alpha\text{-}decay} {}^{235}_{92}U + {}^{4}_{2}He $$

-do not have very great penetrating power compared to other forms of radiation

-passage can be stopped by any shielding such as a few sheets of paper

Emission of particles…

Beta particles ($\boldsymbol{\beta}$ or $_{-1}\boldsymbol{e}^{0}$):

Beta particles are emitted from the nuclei of radio-active isotopes, also at velocities approaching that of light.

$$^{214}_{82}Pb \xrightarrow{\beta\text{-}decay} {}^{214}_{83}Bi + {}^{0}_{-1}e + \vartheta$$

- penetrating power is small compared to γ rays but is larger than that of α particles

Emission of particles…

- **Gamma radiation:**

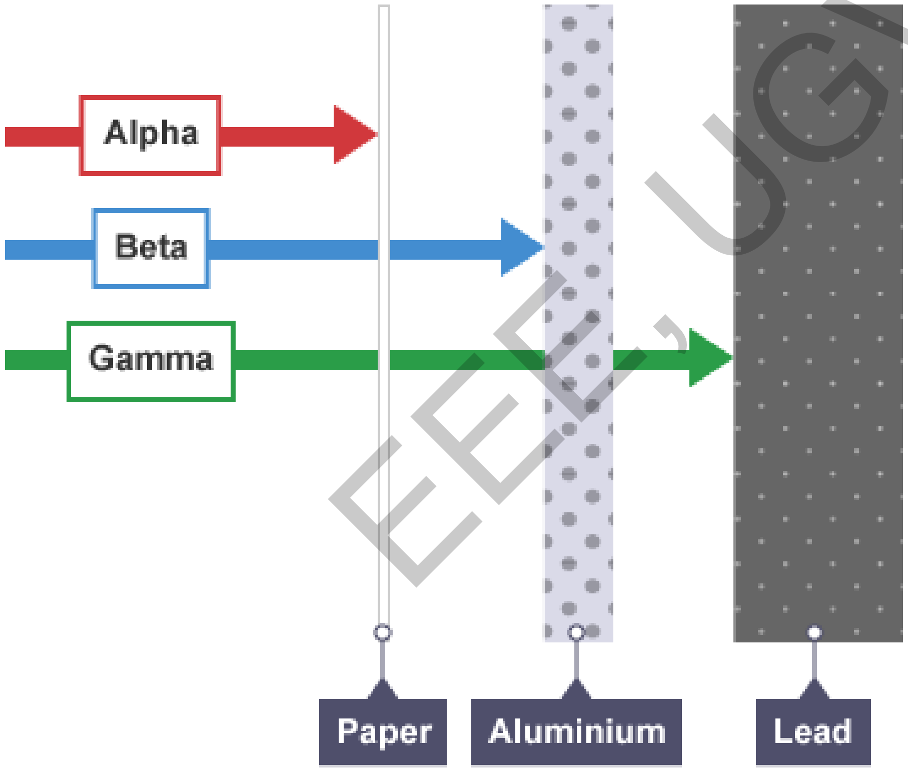
Gamma rays (γ) are electro-magnetic waves. When an $\alpha-or$ a β −particle is expelled from the nucleus of a radioactive element and the smaller nucleus is still in an excited state, it emits the excess energy in the form of γ-radiation.

$$\left[{}_{Z}^{A}X\right]^{*} \longrightarrow \left[{}_{Z}^{A}X\right] + \gamma$$

-shorter wavelength
-possess a very high energy level

Positron decay (positive beta), K capture, Neutron emission

Emission of particles…



Difference between chemical and nuclear reaction

- Atoms are **combined or separated** in a chemical reaction. Small energy is released.

$$C + O_2 = CO_2$$

- While **nuclear reaction takes place in the atom's nucleus**, the electrons in the atom are responsible for chemical reactions.
- Chemical reactions involve the **transfer, loss, gain and sharing of electrons** and nothing takes place in the nucleus. Nuclear reactions involve the decomposition of the nucleus and have **nothing to do with the electrons.**
- In a nuclear reaction, the protons and neutrons react **inside the nucleus** and in chemical reactions the **electrons react outside the nucleus.**
- When comparing the energies, a chemical reaction involves only **low energy** change, whereas a nuclear reaction has **a very high energy change.**

Nuclear stability and binding energy

- Mass defect:

The sum of the masses of the protons and neutrons that comprise the nucleus exceeds the mass of the atomic nucleus. This difference in mass is called the **mass defect.**

$$\Delta m = n_n \, m_n + (m_p + m_e)Z - {}_Z m^A$$

where n refers to the number and m the mass of particles. The mass defect is converted to energy in a nuclear reaction as given by Einstein's law:

$$\Delta E = \Delta m \cdot C^2$$

where E = energy, J; C = velocity of light = 3×10^8 m/s; and Δm = mass defect, kg.

Nuclear stability and binding energy…

Binding energy:

- The energy associated with the mass defect is known as the binding energy (BE) of the nucleus.
- It acts as a "glue" which binds the protons and neutrons together in the nucleus.

The energy equivalent of 1g of mass is

$$\Delta E = 1 \times 10^{-3}\ \text{kg} \times (3 \times 10^{8}\ \text{m/s})^{2} = 9 \times 10^{13}\ \text{J}$$

Nuclear stability and binding energy…

Similarly, the energy equivalent of 1 amu of mass is

$$\Delta E = 1.66 \times 10^{-27}\ \text{kg} \times (3 \times 10^{8}\ \text{m/s})^2$$
$$= 14.94 \times 10^{-11}\ \text{J} = 9.31 \times 10^{8}\ \text{eV}$$
$$= 931\ \text{MeV}$$

Therefore, if 1 amu of mass could be completely converted to energy, 931 MeV would be yielded.

Nuclear stability and binding energy…

- **Nuclear stability**

The binding energy per nucleon (i.e., proton and neutron) determines the stability of the nucleus.

Let us consider a helium nucleus as a simple example.

$$\text{He nucleus: } 2\,{}_0n^1 + 2\,{}_1p^1 \longrightarrow {}_2\text{He}^4$$

Experimental mass of helium atom – mass of two orbital electrons = 4.00387 – 2×0.00055 = 4.00277 amu

$$\text{Calculated mass} = 2\,m_p + 2m_n = 2 \times 1.00759 + 2 \times 1.00898$$
$$= 4.03314 \text{ amu}$$

Mass defect, Δm = 4.03314 - 4.00277 = 0.03037 amu

Binding energy, ΔE = 0.03037 × 931
= 28.2 MeV

Binding energy/nucleon = 28.2/4
= 7.05 MeV

Fusion and Fission

- Fusion

By combining light nuclei, the process being known as fusion.

- Fission

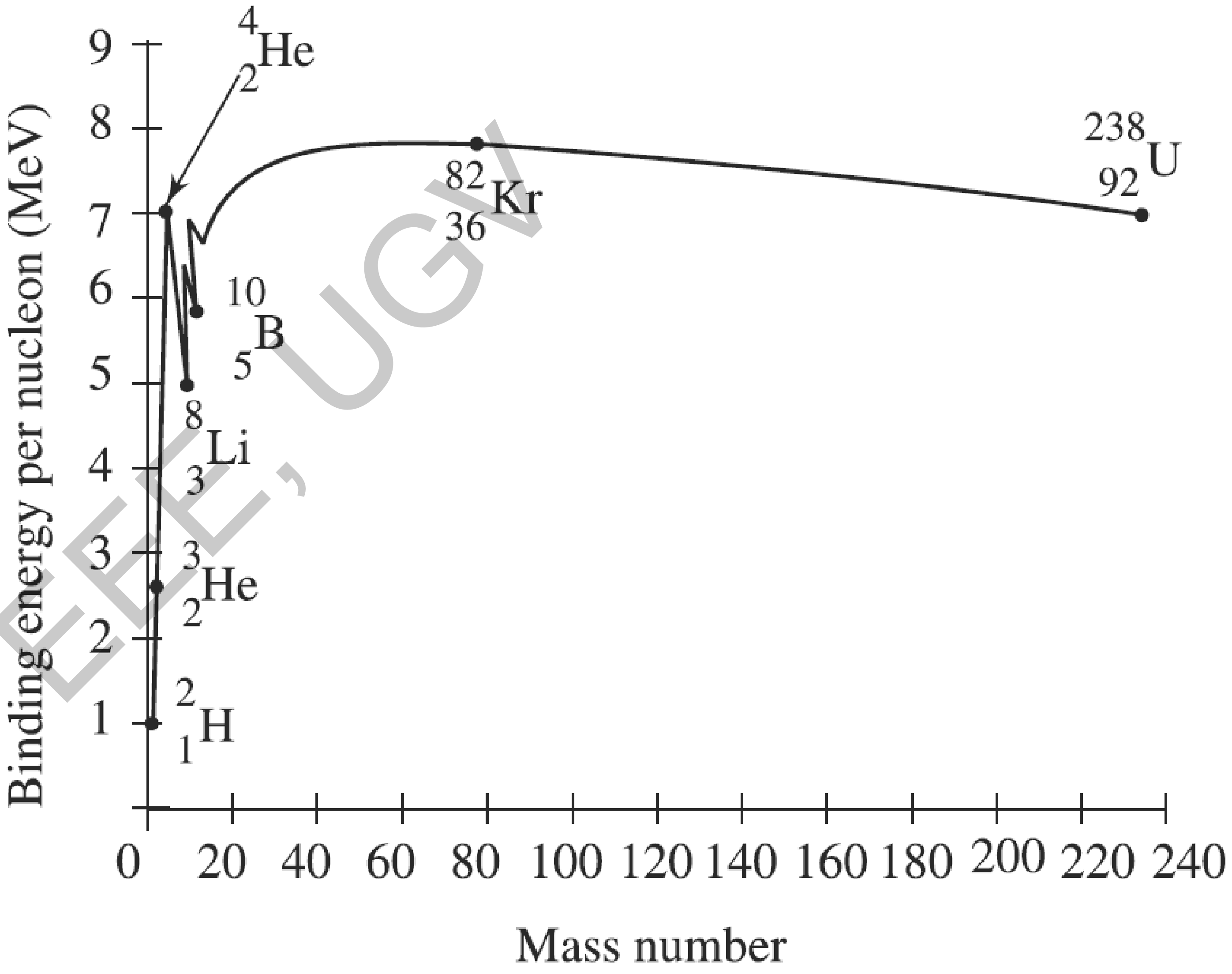
By breaking up heavy nuclei into the nuclei of intermediate size, the process being known as fission.

Nuclear stability and binding energy...

Higher the binding energy per nucleon, higher is the stability of the nucleus.

The binding energy curve shows that the most stable elements (like iron, cobalt, nickel etc.) are in the intermediate mass number range. If elements of low mass number are fused together, it would lead to more stable elements. The elements of higher mass number are less stable and if they are fissioned, they would form elements of less mass number, which are more stable.

Thus light isotopes like hydrogen, deuterium and so on are good for fusion reactions, while the heavier isotopes like uranium are suitable for fission reaction.



Binding energy per nucleon varying with mass number

Nuclear stability and binding energy…

- For most medium and heavy nuclei, the binding energy per nucleon falls roughly between 7.5 and 8.7 MeV. Thus, if a nucleus is to expel one nucleon, say a neutron, it should first have a minimum excitation energy of between 7.5 and 8.7 MeV. Only in such an excited state a nucleus can emit a neutron.

Reasons behind nuclear stability

- Higher binding energy per nucleon results in higher stability.
- The nuclei of the even-even type, i.e., having an even number of protons and even number of neutrons, are very stable. Therefore, a 146 → ${}^{238}_{92}U$ atom having 92 protons and 146 neutrons is quite stable and requires very high energy neutrons for fission, whereas a ${}^{235}_{92}U$ atom having 92 protons and 143 neutrons can be fissioned even by low energy neutrons.
- When there is an excess of neutrons in the nucleus and the neutron/proton ratio is well above unity, instability occurs in elements heavier than Bismuth-209(${}^{209}_{83}Bi$), i.e., nuclei heavier than this are radioactive.

Last class

- **Radioactive emissions**
- **Difference between chemical and nuclear reaction**
- **Mass defect and binding energy**

Decay law/Rutherford and Soddy theory

Suppose that at any time *t* there are *N* radioactive atoms.

Let, the number of atoms *dN* disintegrate in time *dt*

The rate of disintegration ∝ the no. of atoms present

$$\frac{dN}{dt} \propto N$$

$$\Rightarrow \frac{dN}{dt} = -\lambda N$$

where, λ is the radioactive constant

Decay law/Rutherford and Soddy theory…

$$\frac{dN}{N} = -\lambda dt$$

Integrating, $\int \frac{dN}{N} = \int -\lambda dt$

$$\Rightarrow \log_e N = -\lambda t + K \qquad (1)$$

When $t = 0, N = N_0, where\ N_0$ is the no. of atoms originally present

$$\log_e N_0 = K$$

From (1),

$$\log_e N = -\lambda t + \log_e N_0$$

$$\Rightarrow \log_e \frac{N}{N_0} = -\lambda t$$

$$\Rightarrow \frac{N}{N_0} = e^{-\lambda t}$$

$$\Rightarrow N = N_0 e^{-\lambda t}$$

Half-life period

- The time required for one-half of the radioactive substance to disintegrate.
- Considered as "finger-prints" to identify a radioisotope.

Suppose that, half-life period = T

We know, $N = N_0 e^{-\lambda t}$

$$\Rightarrow \frac{N}{N_0} = e^{-\lambda t}$$

When $N = \frac{N_0}{2}, t = T$

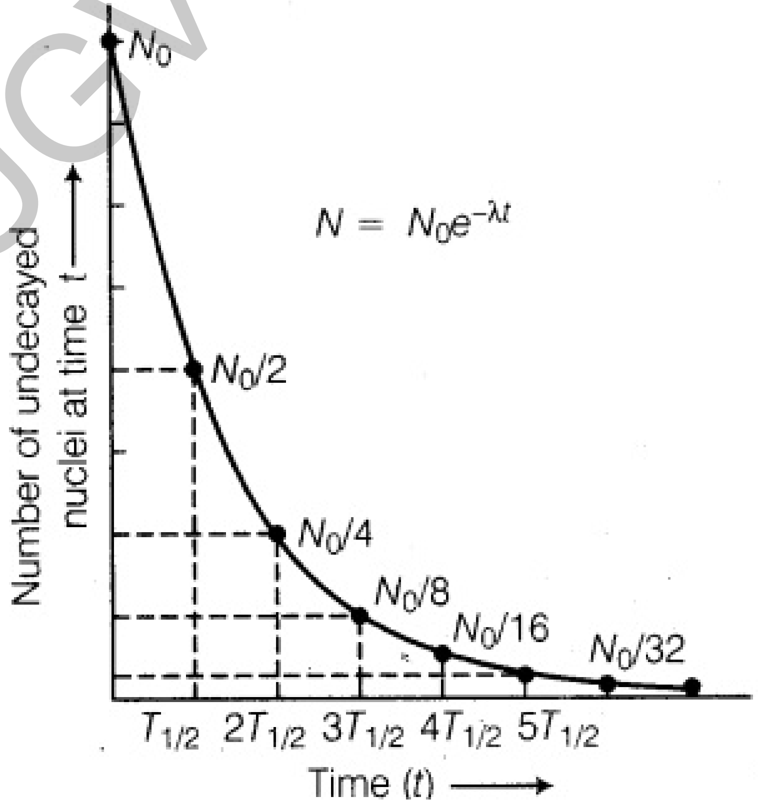
$$\frac{1}{2} = e^{-\lambda T}$$

$$\Rightarrow e^{\lambda T} = 2$$

$$\Rightarrow \lambda T = \log_e 2 = 0.693$$

$$\Rightarrow T = \frac{0.693}{\lambda}$$

$$T \propto \frac{1}{\lambda}$$



Unit of radioactivity

- The unit of radioactivity is Curie (Ci)

$$1 \text{ Curie} = 3.615 \times 10^{10} \text{ dis/s}$$

In SI unit, 1 Becquerel (Bq) = 1 dis/s

Mathematical Problem

A certain radioactive substance has a disintegration constant $\lambda = 1.44 \times 10^{-3}$ per hour. In what time will 75% of the initial number of atoms disintegrate?

Solution:

$$N = N_0 e^{-\lambda t}$$

$$\Rightarrow \frac{1}{4} = e^{-\lambda t}$$

$$\Rightarrow t = \frac{\log_e 4}{\lambda}$$

$$= 962.9\ hours$$

$Here,\ \lambda = 1.44 \times 10^{-3}$ per hour

$$N = N_0 - \frac{3}{4} N_0 = \frac{N_0}{4}$$

t=?

Nuclear reactions

- A nuclear reaction is one which proceeds with a change in the composition of the nucleus so as to produce an atom of a new element.
- The following particles are commonly used to start and accelerate nuclear reactions. These are known as bombardment particles.

Proton, ${}_{1}^{1}H$
Alpha particle, α or ${}_{2}^{4}He$
Deuteron, ${}_{1}^{2}H$
Neutron, ${}_{0}^{1}n$
Gamma rays, γ

Bombardment particles

- Production of alpha particles - bombardment of nitrogen nucleus by a proton.

$$^{15}_{7}N + ^{1}_{1}H \longrightarrow ^{12}_{6}C + ^{4}_{2}He$$

- Production of neutron

$$^{9}_{4}Be + ^{4}_{2}He \longrightarrow ^{12}_{6}C + ^{1}_{0}n$$

Advantages of using neutron ($_{0}^{1}n$)

Neutrons are most suitable for fission

- It has no charge (electrically neutral) and thus requires less kinetic energy to flow through matter because it does not produce electrical repulsion.

- It can move through matter for longer distances than charged particles without being stopped.

Methods of producing neutrons

- Particle accelerators such as cyclotrons or Van de Graaff generators speed up charged particles to bombard a target nucleus such as lithium, beryllium, etc. which produces neutron beam.
- Alpha particle reactions, use α-emitters such as radium to bombard a light element such as beryllium or boron.

$$^{9}_{4}Be + ^{4}_{2}He \longrightarrow ^{12}_{6}C + ^{1}_{0}n$$

- Bombardment of a light element such as beryllium by γ-rays.

$$^{9}_{4}Be + ^{0}_{0}\gamma \longrightarrow ^{8}_{4}Be + ^{1}_{0}n$$

- When neutrons are used to produce the fission reaction in nuclear reactors, some more high speed neutrons are emitted during the reaction.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{137}_{56}Ba + ^{97}_{36}Kr + 2\,^{1}_{0}n + \gamma$$

Fertile and Fissile materials

- Fertile materials:

Fertile materials, i.e., those which can be transformed into fissile materials, cannot sustain chain reactions.

Example: U-238, Th-232

Fertile and Fissile materials....

Fissile materials:

When a fertile material is hit by neutrons and absorbs some of them, it is converted to fissile material.

$${}^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{92}U + \gamma$$

$${}^{239}_{92}U \longrightarrow {}^{239}_{93}Np + {}^{0}_{-1}e$$

$${}^{239}_{93}Np \longrightarrow {}^{239}_{94}Pu + {}^{0}_{-1}e$$

$${}^{232}_{90}Th + {}^{1}_{0}n \longrightarrow {}^{233}_{90}Th + \gamma$$

$${}^{233}_{90}Th \longrightarrow {}^{233}_{91}Pa + {}^{0}_{-1}e$$

$${}^{233}_{91}Pa \longrightarrow {}^{233}_{92}U + {}^{0}_{-1}e$$

Energy from fission and fuel burn up

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{137}_{56}Ba + ^{97}_{36}Kr + 2^{1}_{0}n$$

$$235.0439+1.00867 \longrightarrow 138.9061+96.9212+2\times1.00867$$

$$\Rightarrow 236.0526 \longrightarrow 235.8446 \text{ amu}$$

Thus, there is a reduction in mass, which appears in the form of energy.

Mass defect, $\Delta m = 235.8446 - 236.0526 = -0.208$ amu

$\Delta E = (-0.208)\times 931 = -193.6$ MeV ≈ 200 MeV

The total energy released per fission reaction is about 200 MeV.

Energy from fission and fuel burn up…

- **The complete fission of 1g of *U-235* nuclei thus produces,**

$$\frac{Avogrado\ constant}{Mass\ of\ U-235\ isotope} \times 200\ MeV$$

$$= \frac{6.023\times10^{23}}{235.0439} \times 200\ MeV$$

$$= 5.126 \times 10^{23} MeV$$

$$= 8.19 \times 10^{10} J = 2.276 \times 10^{4} kWh$$

$$= 0.984\ MW - day$$

$$\cong 1 MW - day$$

Thus, a reactor burning of 1g of U-235 generates nearly 1 MW-day of energy.

- **Fuel burnup - the amount of energy in MW-days produced of each metric ton of fuel.**

Neutron energy

$$E_n = \frac{1}{2} m_n V^2$$

$$= 5.23 \times 10^{-13} V^2 \ eV \text{, where V is in cm/s}$$

Classification of neutron

Classification	*Neutron energy (eV)*	*Corresponding velocity (m/s)*
Fast	$> 10^5$	$> 4.4 \times 10^6$
Intermediate	$1\text{–}10^5$	$(1.38 \text{ to } 4.4) \times 10^6$
Slow	< 1	$< 1.38 \times 10^4$

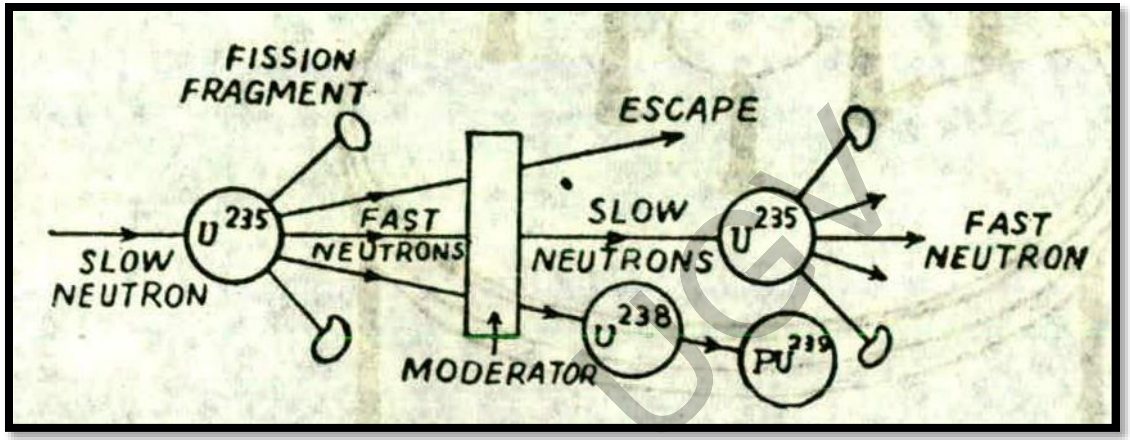
Summary

- **Decay law**
- **Bombardment particles**
- **Energy release per fission**

Last class

- **Decay law & Half-life period**
- **Bombardment particles**
- **Fertile and Fissile materials**
- **Energy from fission and fuel burn up**

Chain reaction



- **When a neutron is captured by a nucleus of an atom of U-235, it splits up roughly into two equal fragments and about 2 or 3 neutrons are released and a large amount of energy (200 MeV) is produced. This is called fission process.**
- **The neutrons so produced are very fast moving neutrons and can be made to fission other nuclei of U-235 thus enabling a chain reaction to take place. When a large number of fissions occurs, enormous amount of heat is produced.**

Chain reaction

The chain reaction producing a constant rate of heat energy can contribute only if the neutron liberated by fission balance the disposal of neutrons by different ways listed below:

1. Escape of neutrons from the fissionable materials
2. Fission capture by U-235, Pu-239 and U-233.
3. Non-fission capture by moderator, control rods, fission fragments and by impurities, etc.

If the neutrons produced in the chain reaction are less than the neutrons disposed off in different ways, the chain reaction will stop.

Chain reaction…

Critical size:

The size of the core for which a chain reaction is possible is called critical size.

Critical mass:

The mass of fuel in such a core is called the critical mass.

If the size of the reactor core is less than a certain minimum, too many fission neutrons escape through its surface and the chain reaction is not sustained.

A **critical mass** is the smallest amount of fissile material needed for a sustained nuclear chain reaction.

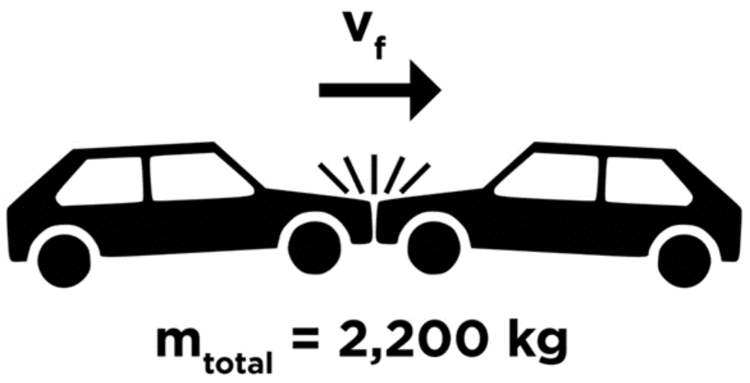
In a reactor using U-235 as fuel, 100/2.47 or about 40.5 of each 100 fission neutrons must ultimately engage in fission to keep the reactor critical. However, only about 84% of the neutrons that get absorbed in U-235 cause fission. The remaining 16% neutrons reacting with it produce U-236 (non-fission capture), an isotope of no particular importance. Therefore, a total of about 40.5/0.84 or 48 neutrons must be absorbed in U-235 to cause fission. Thus, a maximum of about 52 neutrons may be allowed to leak out of the core and be absorbed in other core materials.

Scattering

As the neutrons travel through matter, they collide with other nuclei and get slowed down. This process is called scattering. The neutron gives up some of its energy with each successive collision.

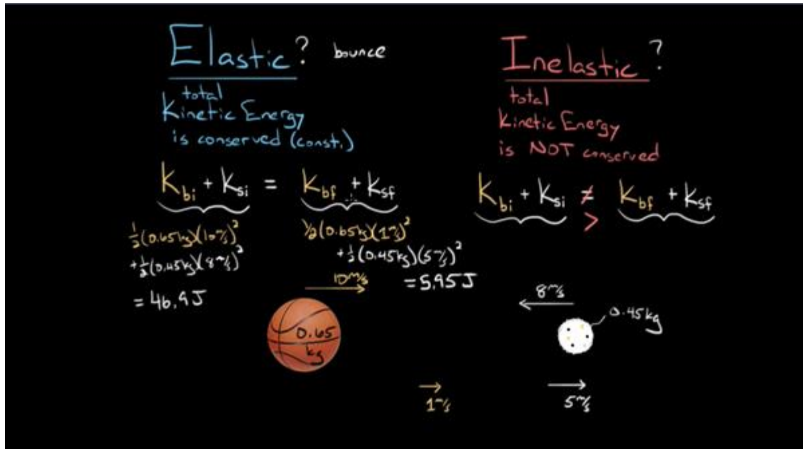
Types:
- **Inelastic scattering**
- **Elastic scattering**

Scattering



Inelastic scattering:

In which momentum and total energy of the particles before and after collision are conserved. However, KE is not conserved.



- Elastic scattering
- An elastic collision is a collision in which there is no net loss in kinetic energy in the system as a result of the collision. Both momentum and kinetic energy are conserved quantities in elastic collisions.

$$(E_n + KE_c)_1 = (E_n + KE_c)_2$$

https://www.khanacademy.org/science/high-school-physics/linear-momentum-and-collisions/inelastic-collisions/v/elastic-and-inelastic-collisions

Neutron scattering

- The average neutron energy lost per elastic collision is expressed in the terms of a quantity called the logarithmic energy decrement, ξ.

Average energy lost per elastic $= \ln E_{n,i} - \ln E_{n,av} = \ln \frac{E_{n,i}}{E_{n,av}}$

where $E_{n,av}$ is the average energy of the neutron after a single collision. ξ is given by

$$\xi = 1 - \left[\frac{(A-1)^2}{2A} ln \frac{A+1}{A-1}\right]$$

Moderator

- A moderator is used to slow down the neutron in a reactor. Thus, smaller the nucleus, better the moderator.

Table the values of n to bring down the neutron energies from 2 MeV to 0.025 eV in elastic collisions. However, n is not the sole criterion of moderator effectiveness. Other aspects, such as the probability of collision, the probability of absorption and scattering, as well as the number of moderator nuclei in a given volume also influence the moderator effectiveness.

Nucleus	*A*	ξ	*n*
H	1	1.000	18
D	2	0.725	25
Be	9	0.208	86
C	12	0.158	114
Al	27	0.074	246
Fe	56	0.038	472
Zr	91	0.021	866
U	238	0.004	4480

Logarithmic energy decrement

- The number of collisions, n, required to slow down a neutron from initial energy, $E_{n,i}$, to a final energy, $E_{n,f}$, in elastic scatter is given by

$$n = \frac{ln\frac{E_{n,i}}{E_{n,f}}}{\xi}$$

Problem

- A newly born neutron of 4.8 MeV is to be slowed to 0.025 eV in a graphite moderator. Assuming all collisions to be elastic, calculate the logarithmic energy decrement representing the neutron energy loss per elastic collision and the number of collisions necessary.

12

$$\xi = 1 - \left[\frac{(A-1)^2}{2A} ln \frac{A+1}{A-1}\right]$$

$$E_{n,i} = 4.8 \text{ MeV}$$

$$E_{n,f} = 0.025 \text{ eV}$$

$$n = \frac{ln \frac{E_{n,i}}{E_{n,f}}}{\xi}$$

Thermal neutrons

When a large number of neutrons are slowed down in a medium, such as a moderator, the lowest energies that they can attain are those that put them in thermal equilibrium with the molecules of that medium. In this state (ground state), they become thermalized and are called thermal (or slow) neutrons.

Thermal reactor:

A reactor primarily utilizing thermal neutrons for fission is called a thermal reactor.

The most probable velocity of a neutron

$$V_m = \left[\frac{2KT}{m_n}\right]^{1/2}$$

where,

K = Boltzmann constant

m_n = Mass of neutron

T = Absolute temperature

$$= \left[\frac{2 \times 1.38 \times 10^{-23} \times T}{1.674 \times 10^{-27}}\right]$$

$$= 128.4\ T^{1/2}\ \text{m/s}$$

The velocity of a thermal neutron depends on only temperature.

Thermal neutrons…

The most probable kinetic energy of a neutron will be

$$KE_m = \frac{1}{2} m_n V_m^2$$

$$= \frac{1}{2} \times \frac{1.674 \times 10^{-27} \times (128.4)^2 T}{1.6021 \times 10^{-19}} \ eV$$

$$= 8.613 \times 10^{-5} \ T \ eV$$

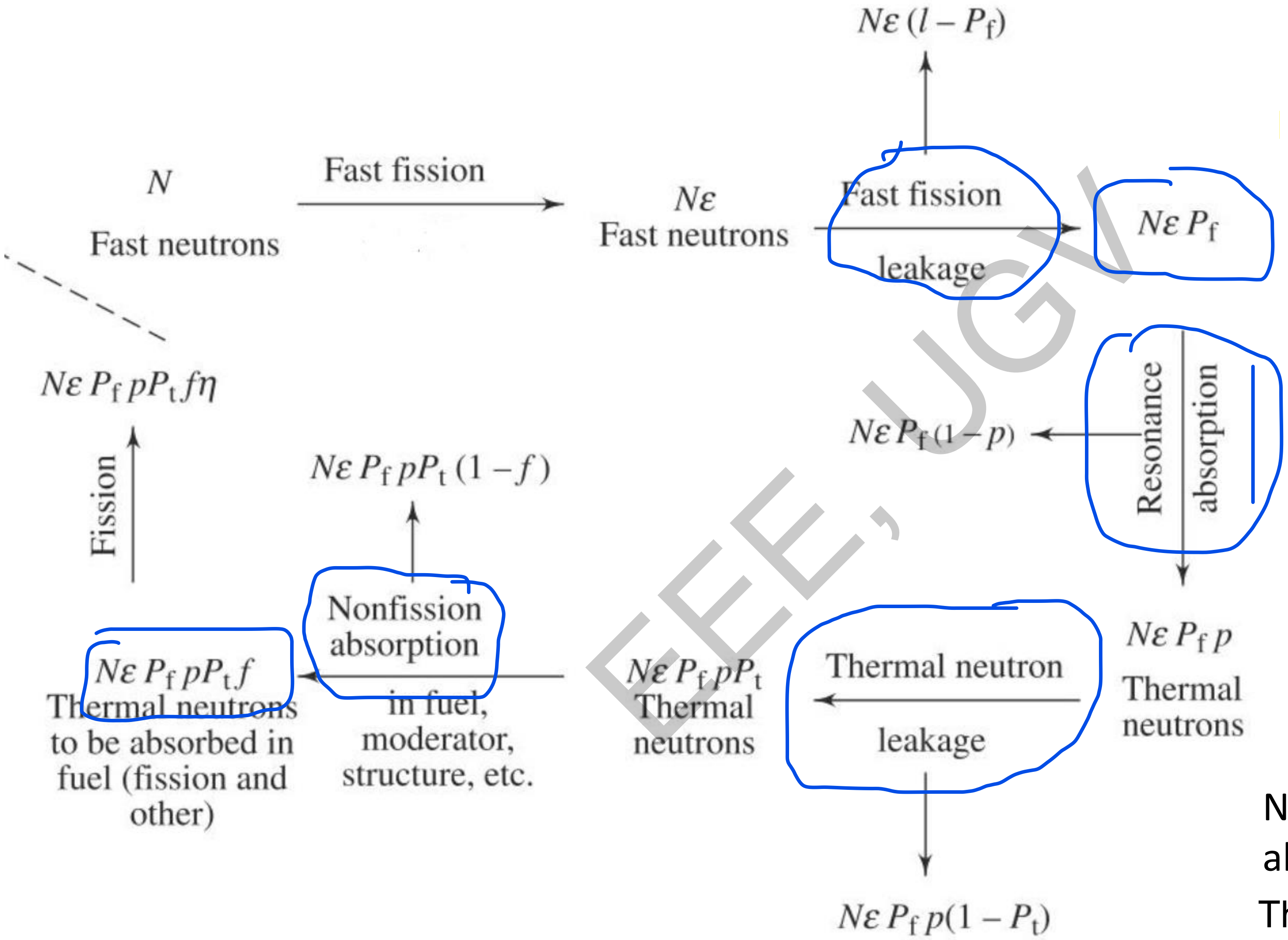
Epithermal neutrons

Neutrons having energies greater than thermal such as those slowing down in a thermal reactor are called epithermal neutrons.

Neutron life cycle

- In a reactor core, neutrons are born at all times and in all places having fissionable material and diffuse in all directions. We will examine the life cycle of a group of neutrons, all assumed to be born at the same time, which undergo scatter, leakage, absorption and other reactions, and finally cause fission and attain the same energy levels simultaneously. This group of neutrons is called a **generation**.
- The series of events or processes that such a group of neutrons undergoes from birth until a new generation is born by fission is called a **life cycle of neutrons**.

Neutron life cycle…



Neutron life cycle in a thermal reactor

Each fission produces about 2.47 new fast neutrons.

Fast fission factor, ε .

The fraction of neutrons that remains within the core is called the fast neutron non-leakage probability, P_f, so that $(1 – P_f)$ is the fraction that leaks and may be called fast neutron leakage probability.

Resonance escape probability, p,

P_t, called the thermal neutron non-leakage probability

Thermal utilization factor, f.

Neutrons absorbed in the fuel do not all cause fission.

The number of neutrons produced per neutron absorbed in fuel is called the thermal fission factor, η.

Effective multiplication factor

The ratio of the number of neutrons at the end of one generation to the number at the beginning of that generation is called the effective multiplication factor, k_{eff}.

$$k_{\text{eff}} = \frac{N\varepsilon P_f p P_t f\eta}{N} = \varepsilon Pfp\eta$$

The product of P_f and P_t is substituted by simply P, called the non-leakage probability

Significance:

- $K_{eff} = 1$ (the condition for a steady and stable chain reaction is satisfied and the reactor is said to be critical)
- $K_{eff} > 1$ (the reactor is supercritical and a divergent chain reaction exists in which the neutron density and fission rate increase at an explosive rate as in an atom bomb)
- $K_{eff} < 1$ (the reactor is subcritical and the chain reaction decreases and eventually dies out)

Nuclear Cross Sections

If a group of neutrons travel with the same KE and the corresponding speed is v cm/s and if their volume density in the beam at a particular point is n neutrons/ cm^3, then the product nv is equal to the number of neutrons crossing a unit target area of 1 cm^2 per second and is called the *neutron flux*. ϕ. Therefore,

$$\phi = nv \qquad (9.29)$$

Neutron flux is the product of neutron density and velocity of neutrons.

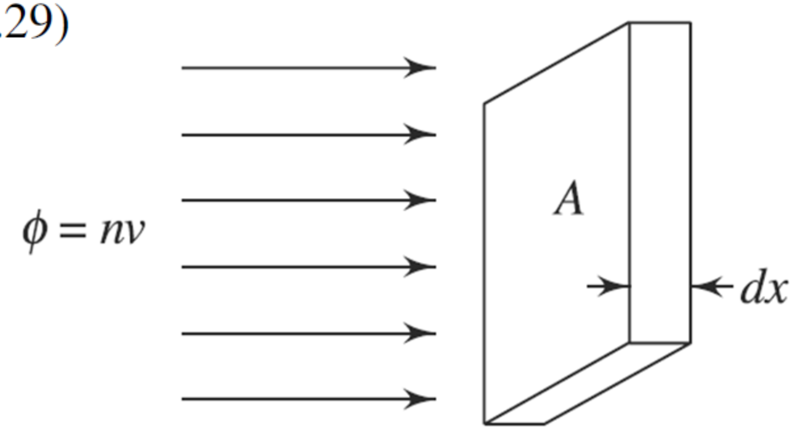


Fig. 9.7 *Interaction rate of neutrons*

Let us consider a beam of neutrons, all of speed V cm/s and density n neutrons/cm^3, incident on a target area of A cm^2 and thickness dx and containing N nuclei/cm^3

Volume = Adx
Total no. of nuclei = $NAdx$

Nuclear Cross Sections…

The interaction rate between a beam of neutrons and the nuclei in a target material has been experimentally observed to be proportional to (i) the neutron flux, and (ii) the number of atoms (or nuclei) in the target.

Interaction rate ∝ neutron flux and no. of nuclei

Interaction rate $\propto \phi N A dx$

Interaction rate $= \sigma \phi N A dx$ (1)

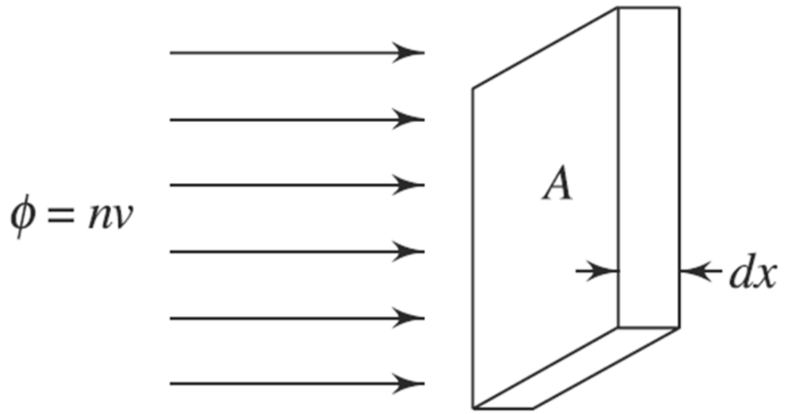


Fig. 9.7 *Interaction rate of neutrons*

σ – proportionality constant, called the microscopic cross section

It is the effective area of the nucleus for interaction with neutrons.

$$1 \text{ barn} = 10^{-24} \text{ cm}^2$$

The total cross section of all nuclei in unit volume of a material is called the macroscopic cross section, Σ.

Macroscopic cross section, $\Sigma = \sigma N$

Nuclear Cross Sections…

$$\text{Interaction rate} = \sigma\phi N A dx \qquad (1)$$

From (1),

Interaction rate = $\phi\Sigma A dx$

Interaction rate/volume = $\phi\Sigma$

The probability that a neutron entering the target will collide or interact within a distance *dx*,

$$= \frac{\sigma\phi N A dx}{\phi A}$$

$$= \sigma N dx$$

$$= \Sigma dx$$

Thus, the macroscopic cross section can be explained as **the probability per unit length that a neutron will collide**, i.e. the collision cross section.

Nuclear Cross Sections…

As the neutrons collide with target nuclei, they get removed from the group. For neutrons which survive collision in an element of thickness dx,

Rate of collision = neutron flux (in–out) A

$$\sigma \phi N A \, \mathrm{d}x = -A \, \mathrm{d}\phi$$

The negative sign indicates that the flux is decreasing. Rearranging,

$$\frac{\mathrm{d}\phi}{\phi} = -\sigma N \, \mathrm{d}x = -\Sigma \, \mathrm{d}x$$

Nuclear Cross Sections…

Integrating, $\int_{\phi_0}^{\phi} \frac{d\phi}{\phi} = -\int_0^x \Sigma dx$

$$\Rightarrow ln\phi - ln\phi_0 = -\Sigma x$$

$$\Rightarrow \ln(\frac{\phi}{\phi_0}) = -\Sigma x$$

$$\phi(x) = \phi_0 e^{-\Sigma x} \qquad (9.37)$$

where ϕ_0 is the incident neutron flux (at $x = 0$). This is referred to as the "survival equation", i.e., the neutron flux which has survived collision after traveling a distance x in the target.

Nuclear Cross Sections…

The average distance that a neutron travels without making a collision or interaction with a target nucleus is called the mean free path, λ,

$$\lambda = \frac{\int_0^\infty x \mathrm{d}\phi(x)}{\phi_0}$$

$$\phi(x) = \phi_0 e^{-\Sigma x}$$

$$\lambda = \frac{\int_0^\infty x(-\phi_0 e^{-\Sigma x}\Sigma)\mathrm{d}x}{\phi_0} = \frac{1}{\Sigma} \tag{9.38}$$

Thus, the mean free path is the reciprocal of the macroscopic cross section.

Moderator

A moderator is used to slow down the neutron in a reactor.

The logarithmic energy decrement factor ξ represents the effect of nucleus size on the average number of collisions required to slow down a neutron over a prescribed energy range.

The hydrogen moderator would slow a neutron from 2 MeV to 0.025 eV in 18 collisions, deuterium in 25 collisions and so on.

However, aspects like the probability of scattering and absorption, and the number of moderator nuclei per unit volume, *N*, are also important.

$$\text{Moderating power} = \xi N\sigma_s = \xi \Sigma_s \quad (9.42)$$

$$\text{Moderating ratio} = \xi \frac{\sigma_s}{\sigma_a} = \xi \frac{\Sigma_s}{\Sigma_a}$$

A high nuclear density *N* is essential since there will be more reactions if there are more nuclei to react. Thus, hydrogen and deuterium are not suitable as moderators, in gaseous forms, instead they are used in light and heavy water. Similarly, when CO_2 is a coolant, graphite is the moderator.

The moderating ratio is a relative measure of the ability of a moderator to scatter neutrons without appreciably absorbing them. It should also be as high as possible for good moderation.

A high value of moderating ratio indicates that the given substance is more suitable for slowing down the neutrons in a reactor.

Moderator…

The selection of a moderator also depends on

- **cost**
- **chemical and structural considerations.**

Heavy water is an excellent moderator, but is extremely costly. Light water is cheap which is used as a coolant and a moderator when enriched uranium is used as fuel.

Graphite is low in cost but is structurally weak. Liquid metal-cooled fast reactors need no moderator.

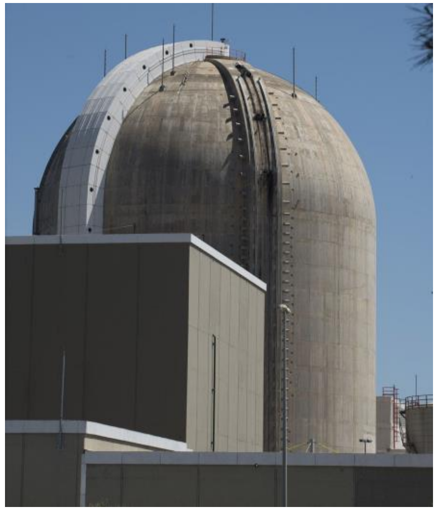
Properties of good moderator

A moderator should process the following properties

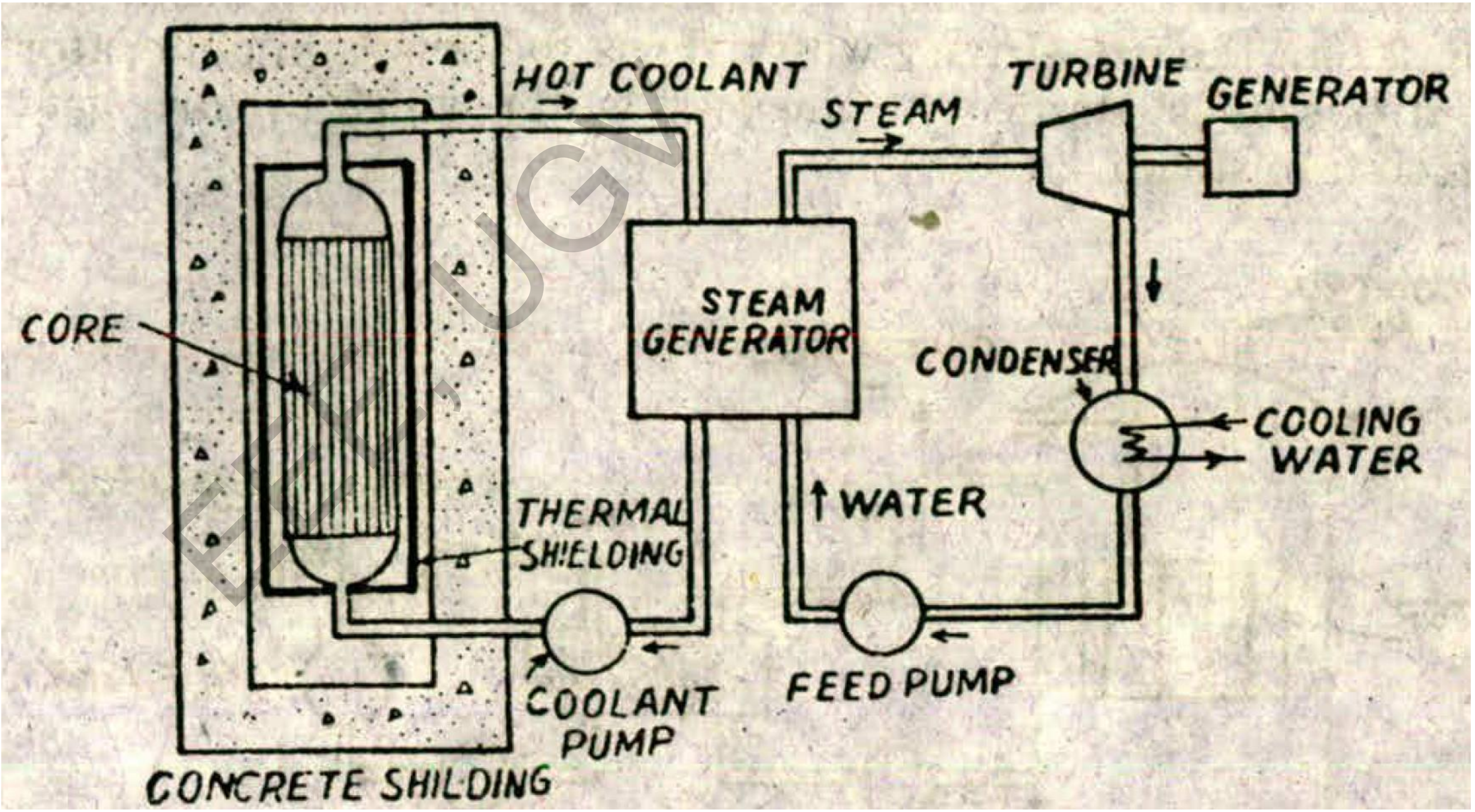
- It should have high thermal conductivity.
- It should be available in large quantities in pure form.
- It should have high melting point in case of solid moderators and low melting point in case of liquid moderators. Solid moderators should also possess good strength and machinability.
- It should provide good resistance to corrosion.
- It should be stable under heat and radiation.
- It should be able to slow down neutrons.

Main components of a NPP

1. Nuclear reactor
2. Heat exchanger (steam generator)
3. Turbine
4. Electric generator
5. Condenser



Containment building

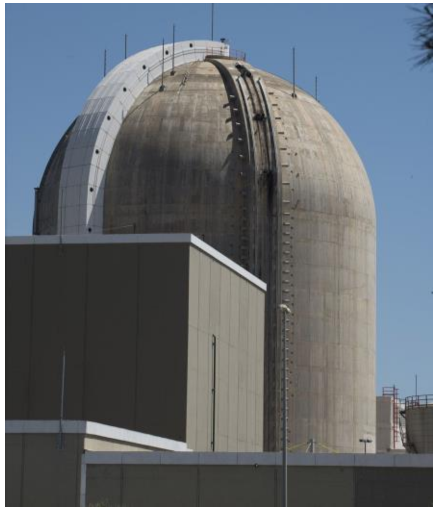


Main components of a NPP…

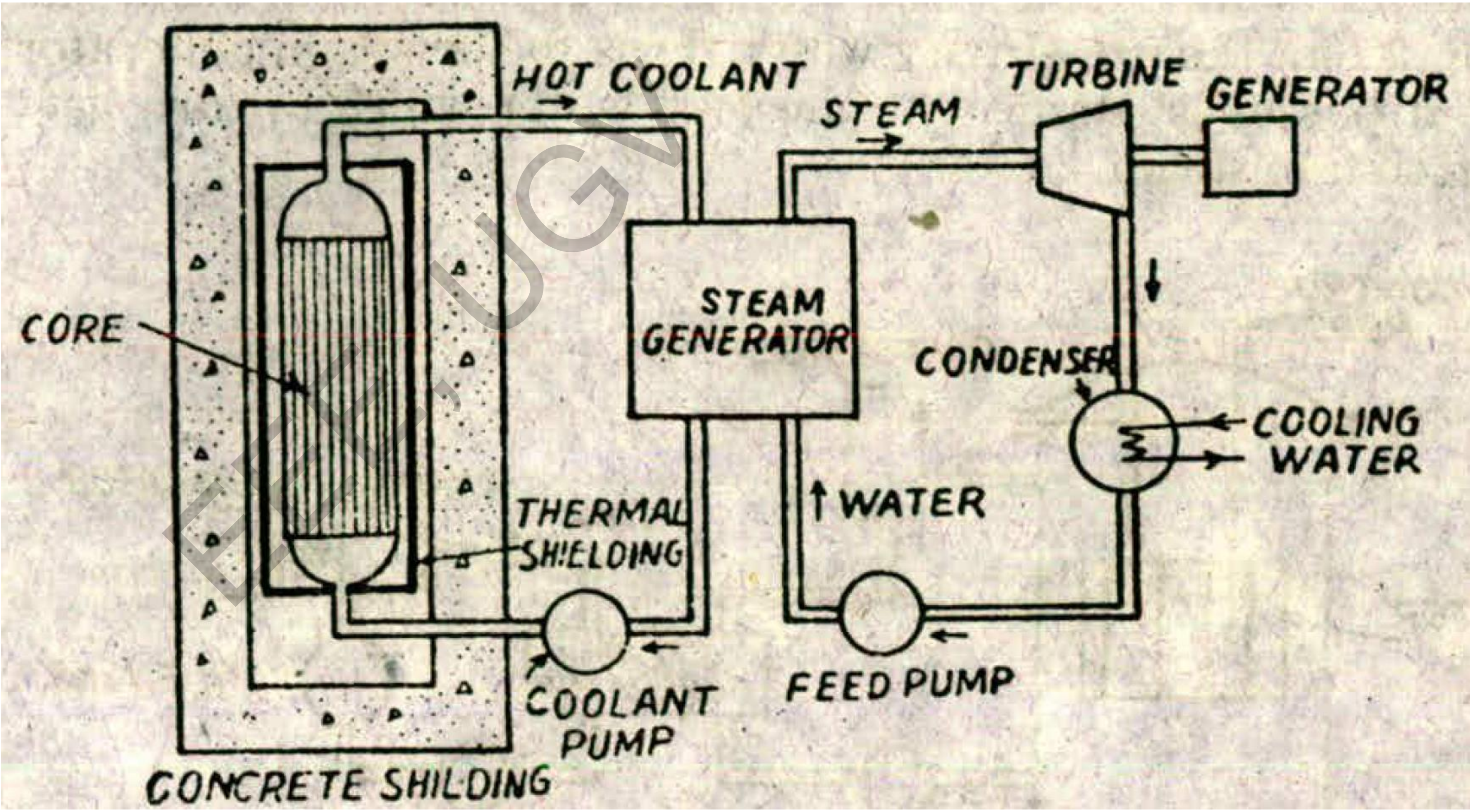
- Reactor of a nuclear power plant is similar to the furnace of steam power plant.
- The heat liberation in the reactor due to the nuclear fission of the fuel is taken up by the coolant circulating through the reactor core.
- Hot coolant leaves the reactor at top and then flows through the tubes of steam generator (boiler) and passes on its heat to the feed water.
- The steam produced is passed through the turbine and after work has been done by the expansion of steam in the turbine steam leaves the turbine and flows to the condenser. Pumps are provided to maintain the flow of coolant, condensate and feed water.

Main components of a NPP

1. Nuclear reactor
2. Heat exchanger (steam generator)
3. Turbine
4. Electric generator
5. Condenser



Containment building



Main parts of a nuclear reactor

A nuclear reactor is an apparatus in which heat is produced due to nuclear fission chain reaction.

- **Reactor core**

Reactor core consists of fuel rods, moderator and space through which the coolant flows.

- **Moderator**

This material in the core is used to moderate or reduce the neutron speeds to a value that increases the probability of fission occurring.

Graphite, Water, etc.

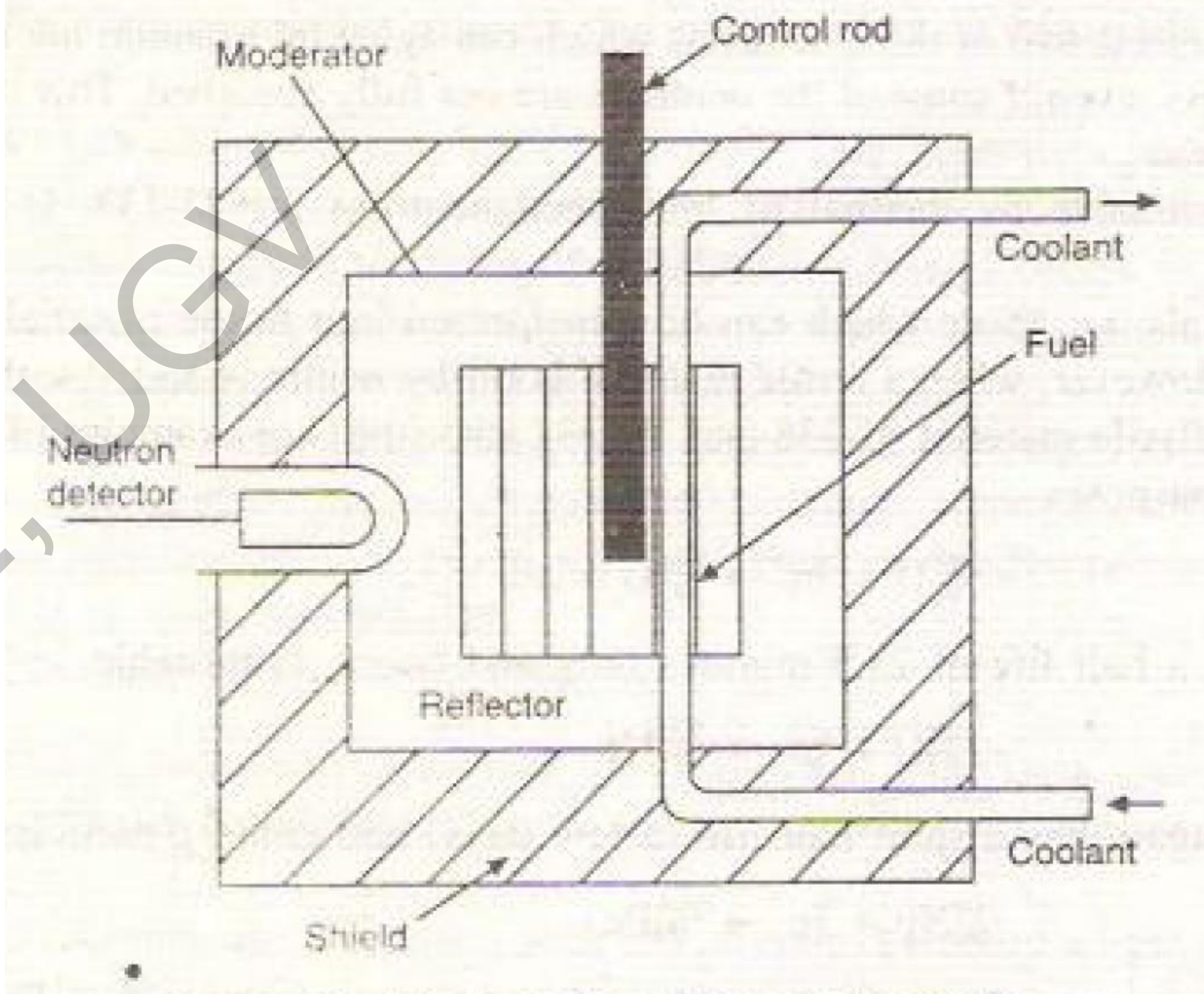


Figure 6.2 Basic components of a nuclear reactor.

Main parts of a nuclear reactor…

- **Reflector**

This completely surrounds the reactor core within the thermal shielding arrangement and helps to bounce escaping neutrons back into the core.

The neutrons produced during the fission process will be partly absorbed by the fuel rods, moderator, coolant or structural material etc. Neutrons left unabsorbed will try to leave the reactor core never to return to it and will be lost. Such losses should be minimized. It is done by surrounding the reactor core by a material called reflector which will send the neutrons back into the core. The returned neutrons can then cause more fission and improve the neutrons economy of the reactor.

Generally the reflector is made up of graphite and beryllium.

Main parts of a nuclear reactor…

- **Shielding**

Shielding helps in giving protection from the deadly α- and β-particle radiations and γ-rays as well as neutrons given off by the process of fission within the reactor.

Thick layers of lead or concrete are provided all round the reactor for stopping the gamma rays.

Thick layers of metals or plastics are sufficient to stop the alpha and beta particles.

Main parts of a nuclear reactor…

Control rods

- The energy produced in the reactor due to fission of nuclear fuel during chain reaction is so much that if it is not controlled properly the entire core and surrounding structure may melt and radioactive fission products may come out of the reactor thus making it uninhabitable.
- This implies that we should have some means to control the power of the reactor. This is done by means of control rods.

Control rods

- absorb excess neutrons,
- keep the chain reaction at a desired level,
- the power of the reactor is controlled by means of control rods,
-made of boron or cadmium.

These rods can be moved in and out of the holes in the reactor core assembly. Their insertion absorbs more neutrons and damps down the reaction and their withdrawal absorbs less neutrons.

Properties of control rods

Main parts of a nuclear reactor…

- **Cooling system**

This removes heat from the core produced by nuclear reaction, the heat being used to generate steam in other apparatus.

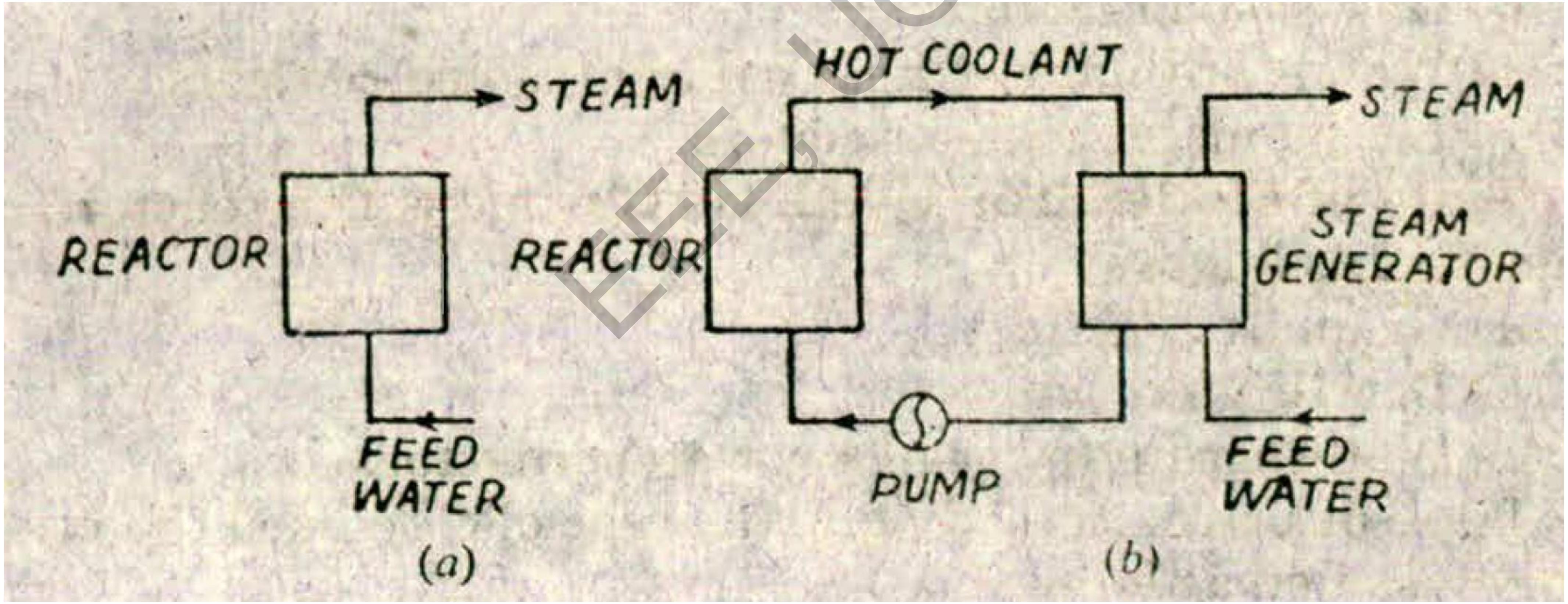
The types of coolants used are carbon di-oxide, air, hydrogen, helium, water, sodium, mixture of sodium, and potassium, etc.

Coolant properties

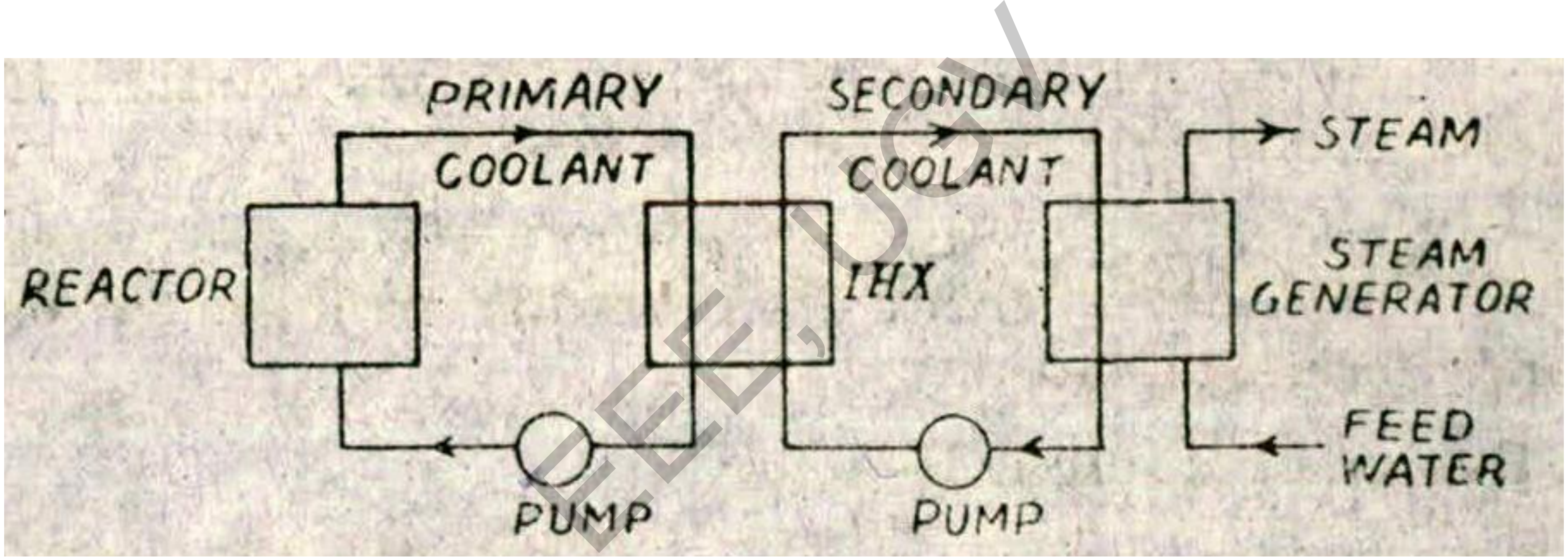
Coolant cycles

The coolant while circulating through the reactor passages take up heat produces due to chain reaction and transfer this heat to the feed water in three ways as follows:

a) direct cycle; b) single circuit system, and c) double circuit system



Coolant cycles…



(c)

Classification of reactor

1) Depending upon the energy of the neutrons:

(a) Fast reactors

(b) Thermal reactors/slow reactors

(c) Intermediate reactors

2) Type of fuel used:

a) Direct

b) Indirect

Nuclear reactors use fissile materials, such as U235, U233, Pu239, as their fuels. Th232 and U238 get converted in fissionable materials like U233 and Pu239, respectively.

Classification of reactor…

3) Types of coolant used:

a) Gas cooled reactor
b) Water cooled reactor
c) Liquid metal cooled reactor

4) Type of moderator used:

a) Graphite reactors
b) Beryllium reactors
c) Water reactors

Classification of reactor…

5) Type of core:

a) Homogeneous reactor

- In this reactor fuel and moderator represent a uniform mixture such as an aqueous solution of a uranium salt.

b) Heterogeneous reactor

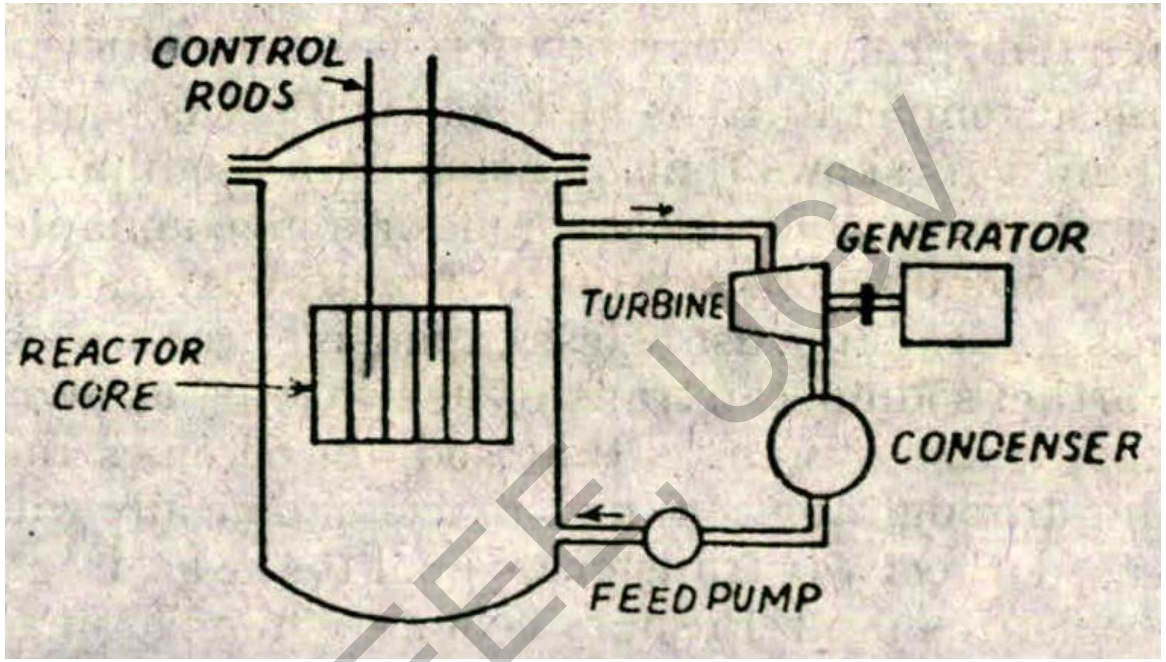
- In such reactor fuel rods are inserted in moderator. The fuel (elements are generally arranged in some regular order forming a lattice).

Design of Nuclear Reactor

The basic factors considered during the design of a nuclear power reactor are as follows:

- Type of reactor
- Type of fuel to be used
- Power rating of reactor in MW
- Coolant system
- Control system
- Rates of neutron production and absorption
- Safety of reactor

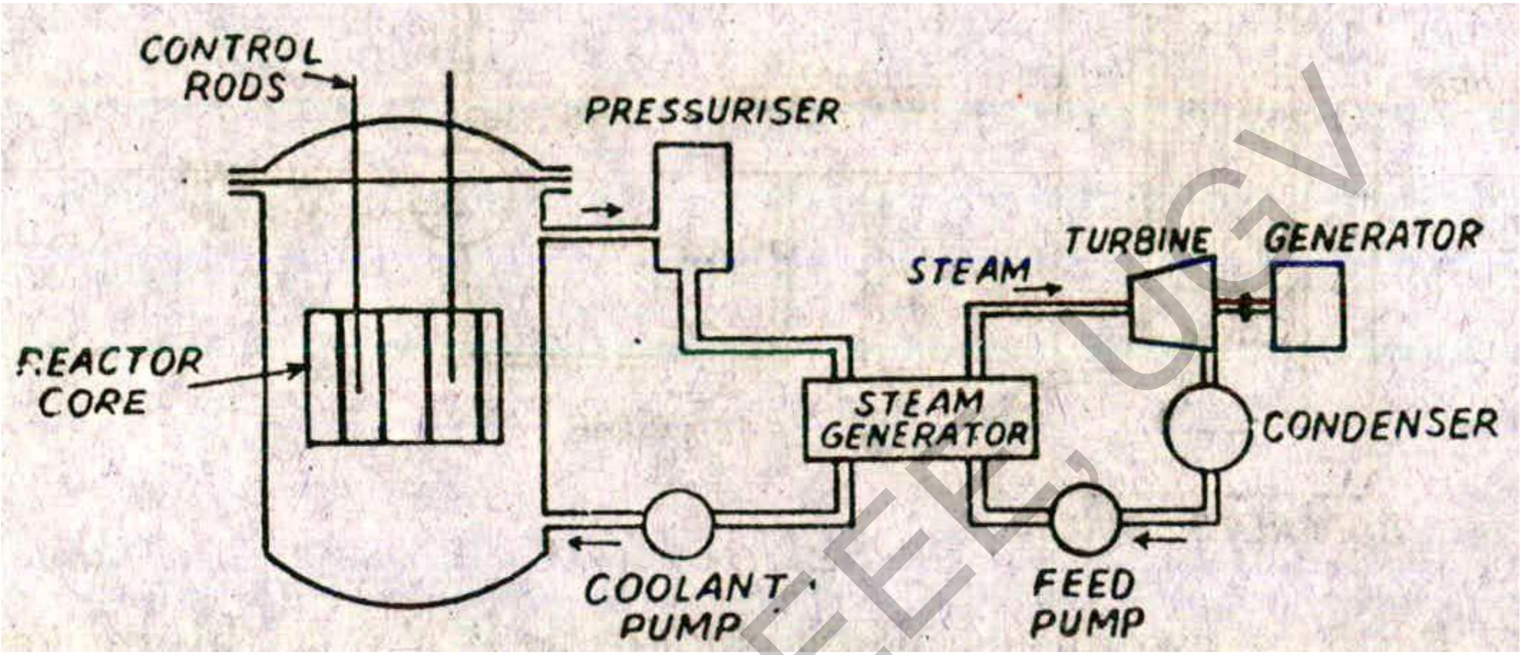
Boiling Water Reactor (B.W.R.)



Enriched uranium (enriched uranium contains more fissionable isotope U235 then the naturally occurring percentage 0.7%) is used as nuclear fuel and water is used as coolant and moderator.

Water enters the reactor at the bottom. It takes up the heat generated due to the fission of fuel and gets converted into steam. Steam leaves the reactor at the top and flows into the turbine.

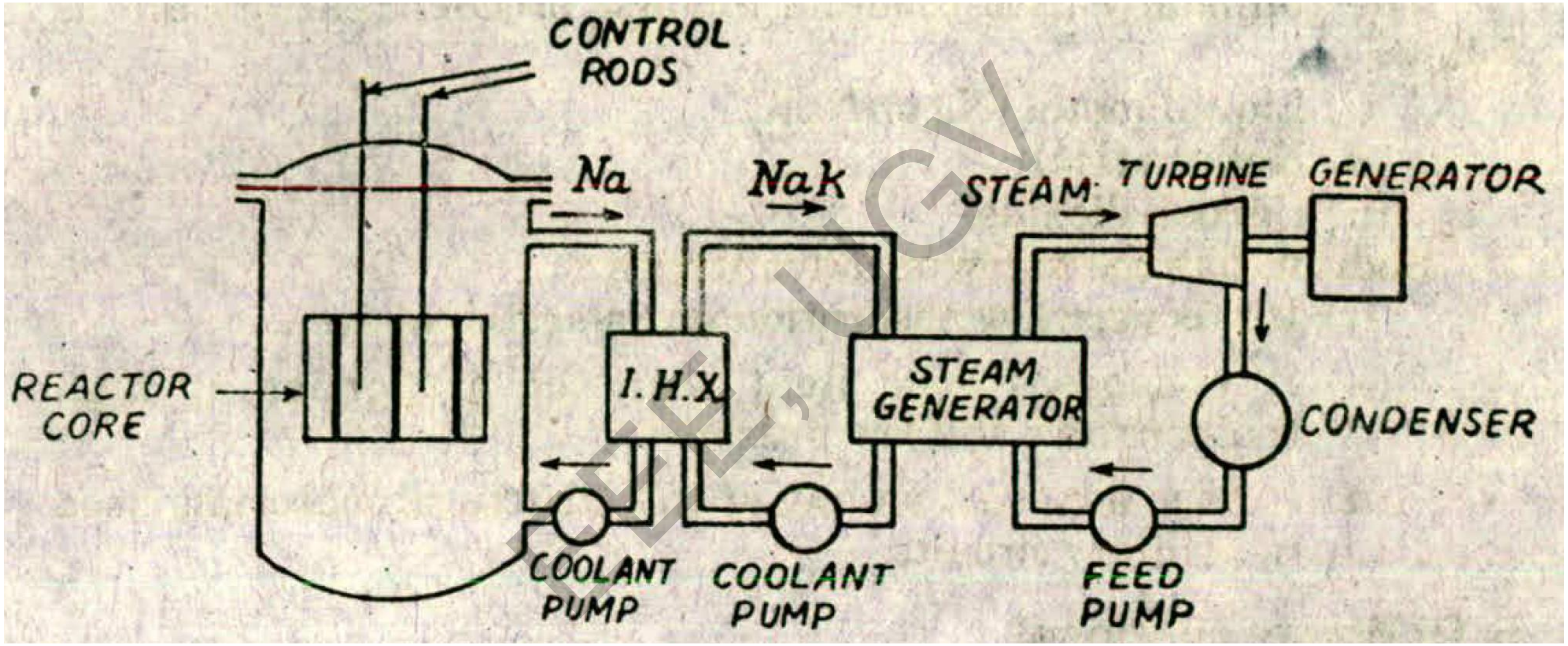
Pressurised Water Reactor (P.W.R.)



A PWR power plant is composed of two loops in series, the coolant loop, called
the primary loop, and the water–steam or working fluid loop.

It uses enriched U as fuel. Water is used as coolant and moderator.
In order that water may not boil (due to its low boiling point 212° F at atmospheric conditions) and remain in liquid state it is kept under a pressure of about 1200 p.s.i.g. by the pressurizer. This enables water to take up more heat from the reactor. From the pressurizer, water flows to the steam generator where it passes on its heat to the feed water which in turn gets converted into steam.

Sodium Graphite Reactor (SGR)



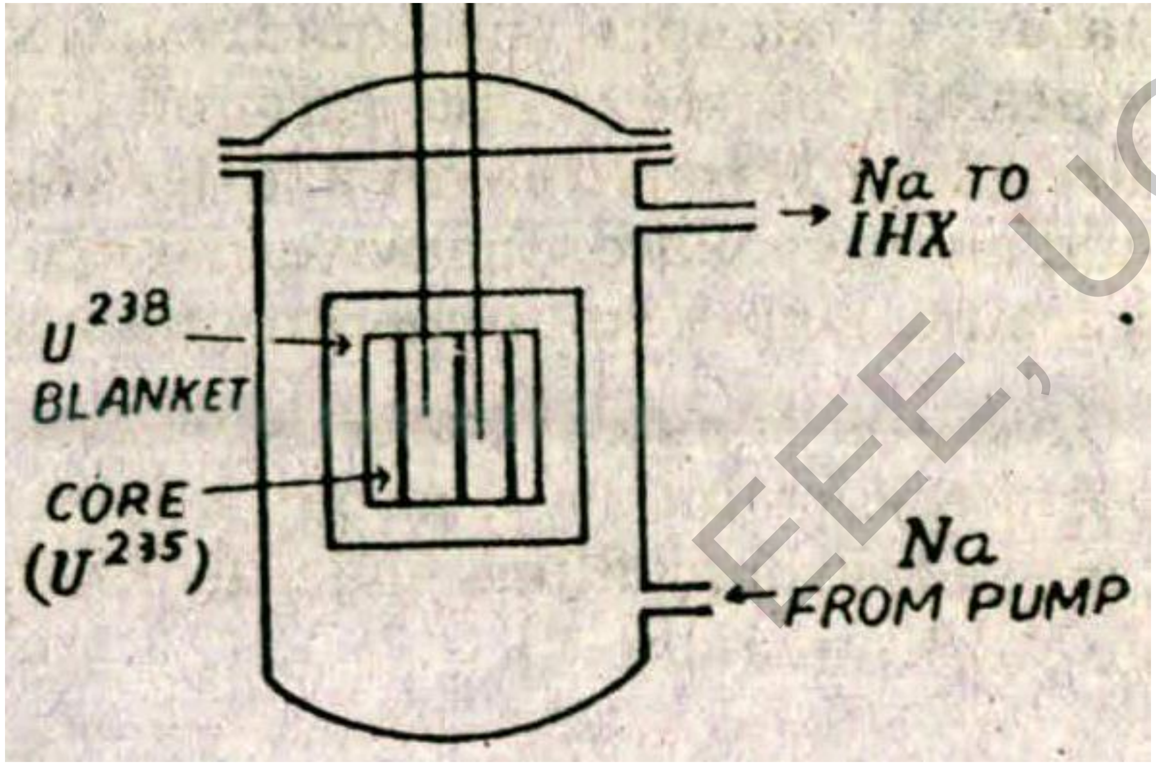
It uses two liquid metal coolants. Liquid sodium (Na) serves as the primary coolant and an alloy of sodium potassium (NaK) as the secondary coolant.

Conservation Ratio

- It is defined as the ratio of number of secondary fuel atoms to the number of consumed primary fuel atoms. A reactor with a conversion ratio above unity is known as a breeder reactor. Breeder reactor produces more fissionable material than it consumes. If the fissionable material produced is equal to or less than the consumed, the reactor is called converter reactor.

Fast breeder reactors are designed to create or breed new fissile material, while producing useful electric power.

Fast Breeder Reactor (FBR)



In this reactor no moderator is used.

Thus this reactor is important because it breeds fissionable material from fertile material U238 available in large quantities.

It uses two liquid metal coolant circuits

Core region is surrounded by a blanket of fertile U-238.

This blanket region captures neutrons that would otherwise be lost through leakage, thus producing additional fissile material.

Waste Disposal

The wastes produced in a nuclear power plant may be in the form of liquid, gas or solid and each is treated in a different manner:

- **Liquid Wastes**
  - (i) Dilution
  - (ii) Concentration to small volumes and storage

- **Gaseous Wastes**

- **Solid Wastes**

Site Selection

- Availability of water
- Distance from load centre
- Distance from populated area
- Accessibility to site
- Waste disposal
- Safeguard against earthquakes

Problem

- Calculate the fission rate of U235 for producing power of one watt if 200 MeV energy is released per fission of U235.

P = Power = 1 watt

E = Energy released per fission of U235 nucleus

=200 MeV = $200\times 10^{6} \times 1.6 \times 10^{-19}$J = 3.2×10^{-11} Watt-Sec

Fission rate of producing one watt of power $= \frac{P}{E}$

$= \frac{1}{3.2\times10^{-11}}$

$= 3.1 \times 10^{10}$ fissions/sec

See examples of Nagpal book

Power of a Nuclear Reactor

V = Volume, m^3

N = Fuel atoms/m^3

n = Average neutron density, *i.e.* number per m^3

a = Fission cross section

ϕ= Neutron flux

ν = Average speed of neutrons m/sec

$\phi = n \times v$

S = total fuel atoms in reactor = $N.V.$

h = number of incident neutrons per second on fuel atoms

$= S \times \phi = n.v.\,N.V.$

x = Number of neutrons causing fission per second

$= h \times a = n.v.\,N.V.a.$

- Fission cross-section represents the probability of fission per incident neutron. For example if y is the number of incident neutron then those causing fission = *a* y

Power of a Nuclear Reactor

Now 3.1×10^{10} fission per second produce a power of one watt

P = Power of nuclear reactor

$$= \frac{x}{3.1 \times 10^{10}} = \frac{n.v.N.V.a.}{3.1 \times 10^{10}} \text{ watts}$$

Mass per atom of U^{235}

$$= \frac{\text{At. weight of } U^{235}}{\text{Avogadro Number}} = \frac{235}{6.02 \times 10^{26}} \text{ kg.}$$

Mass of NV atoms = $N.V.$ × Mass per atom

$$= NV \times \frac{235}{6.02 \times 10^{26}} = M \text{ kg (say)}$$

Now $$P = \frac{n.v.N.V.a.}{3.1 \times 10^{10}} \text{ watts}$$

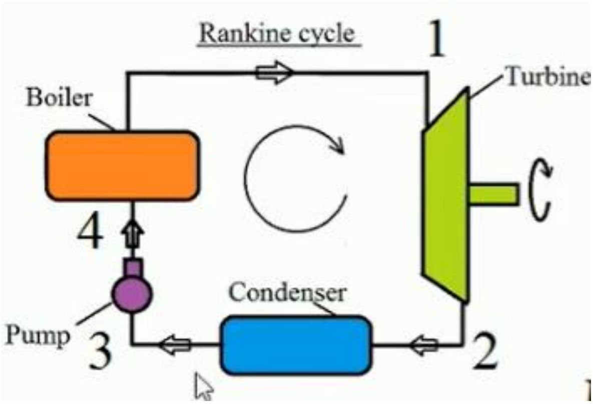
$$= \frac{\phi \times 6.02 \times 10^{26} M \times 582 \times 10^{-28}}{3.1 \times 10^{10} \times 235}$$

$$= 4.8 \times 10^{-12} M\phi \text{ watts.}$$

Thermal Power Station

- A thermal power station is a power station in which **heat energy is converted to electricity.**

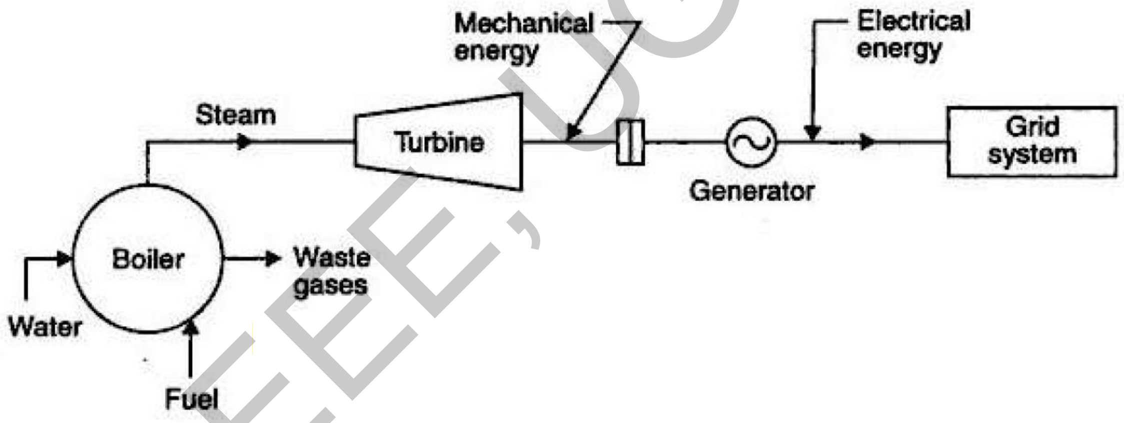
- Typically, water is heated into steam, which is used to drive an electrical generator. After it passes through the turbine the steam is condensed in a steam condenser and recycled to where it was heated. This is known as a Rankine cycle.



- The greatest variation in the design of thermal power stations is due to the different heat sources: fossil fuel, nuclear energy, solar energy, biofuels, and waste incineration are all used.

Coal-fired Thermal Power Station

A generating station which converts the **heat energy of coal combustion** into electrical energy is known as a coal-fired thermal power station.



Steam is produced in the boiler utilizing the heat of coal combustion. The steam is then expanded in the prime mover (i.e. steam turbine) and is condensed in a condenser to be fed into the boiler again. The steam turbine drives the alternator which converts mechanical energy of the turbine into electrical energy.

Advantages

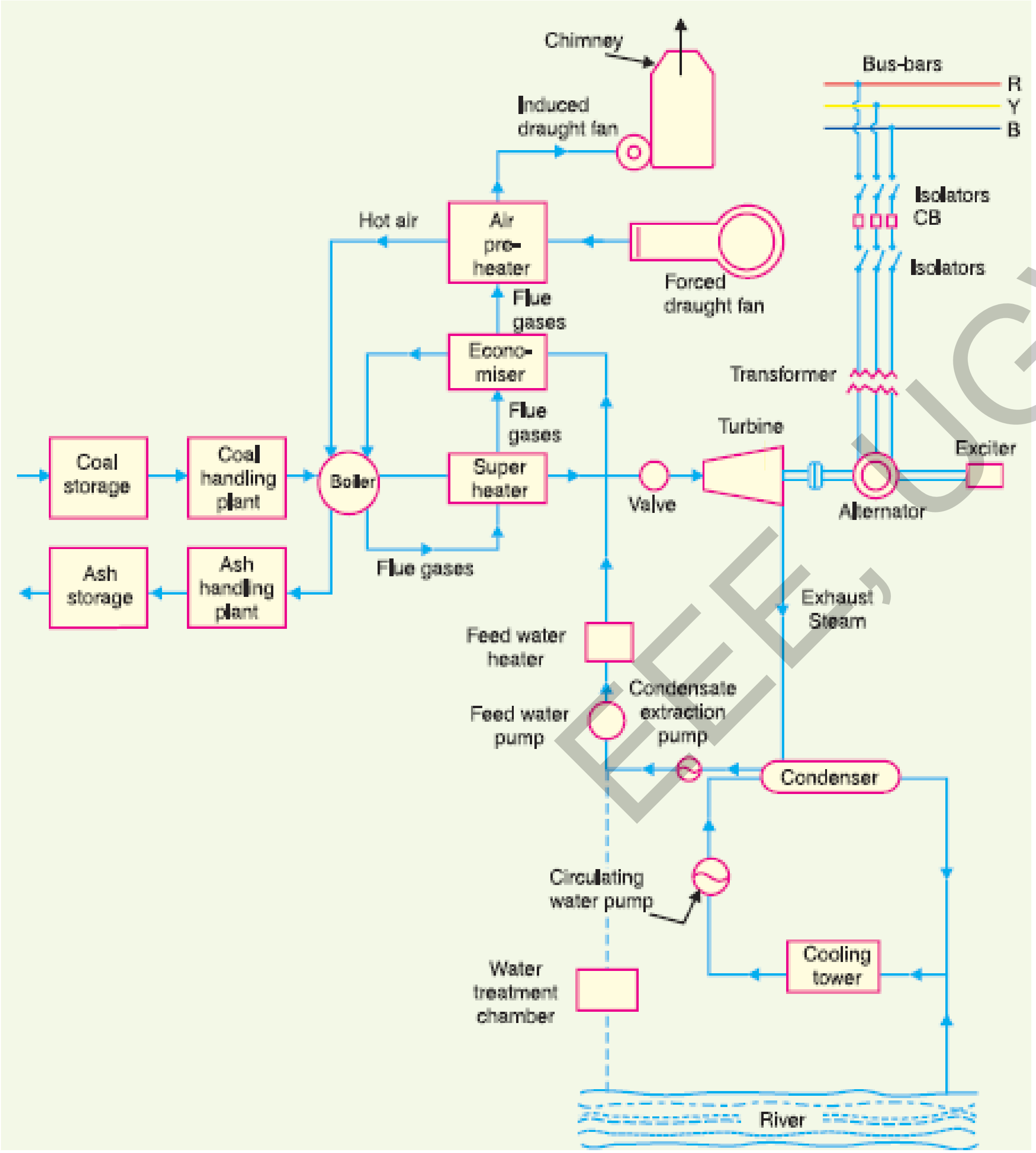
- **The fuel (i.e., coal) used is quite cheap.**
- **Less initial cost as compared to other generating stations.**
- **It can be installed at any place irrespective of the existence of coal. The coal can be transported to the site of the plant by rail or road.**
- **It requires less space as compared to the hydroelectric power station.**
- **The cost of generation is lesser than that of the diesel power station.**

Disadvantages

- **It pollutes the atmosphere due to the production of large amount of smoke and fumes.**

- **It is costlier in running cost as compared to hydroelectric plant.**

Schematic Arrangement

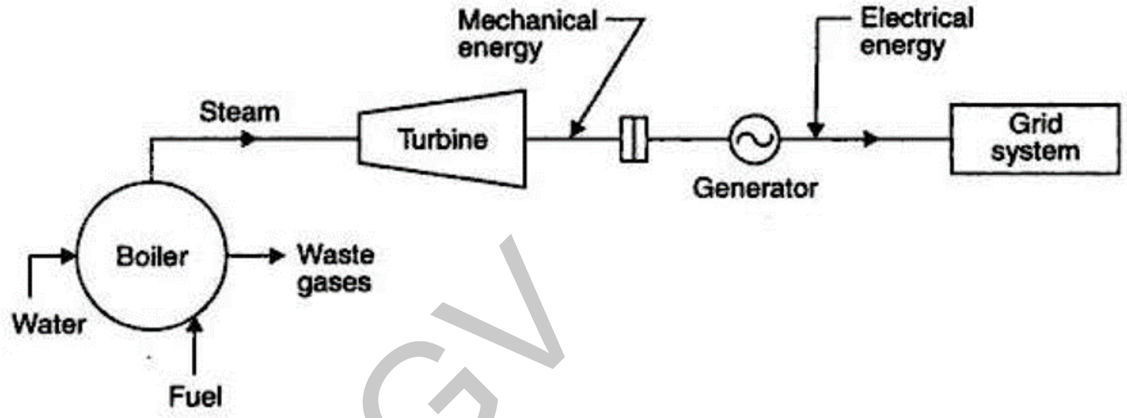


- ❖**Coal and ash handling arrangement**
- ❖**Steam generating plant**
  - a. **Boiler**
  - b. **Superheater**
  - c. **Economizer**
  - d. **Air preheater**
- ❖**Steam turbine**
- ❖**Alternator**
- ❖**Feed water**
- ❖**Cooling arrangement**

Site Selection

- Supply of fuel
- Availability of water
- Transportation facilities
- Cost and type of land
- Nearness to load centres
- Distance from populated area

Efficiency

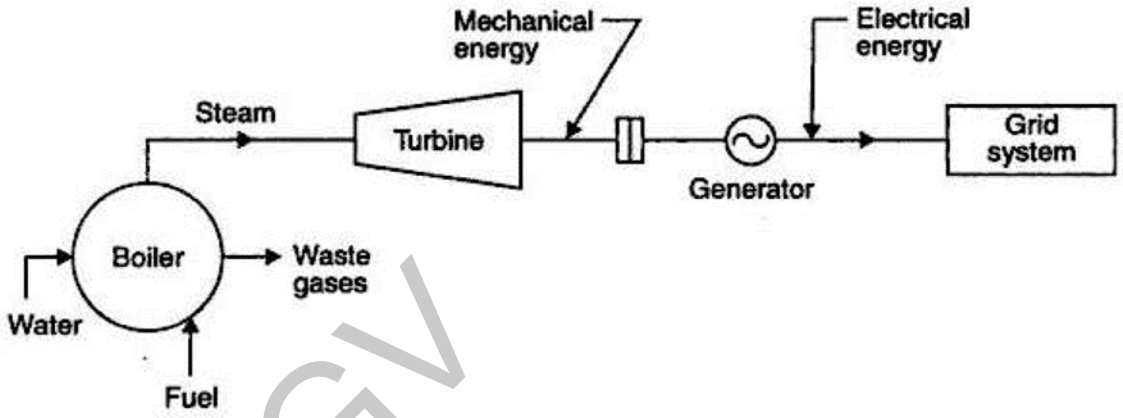


Thermal efficiency:

The ratio of heat equivalent of mechanical energy transmitted to the turbine shaft to the heat of combustion of coal is known as thermal efficiency of steam power station.

$$\text{Thermal efficiency, } \eta_{thermal} = \frac{\text{Heat equivalent of mech. energy transmitted to turbine shaft}}{\text{Heat of coal combustion}}$$

Efficiency…



Overall efficiency:

The ratio of heat equivalent of electrical output to the heat of combustion of coal is known as overall efficiency of steam power station, i.e.,

$$\text{Overall efficiency, } \eta_{overall} = \frac{\text{Heat equivalent of electrical ouput}}{\text{Heat of combustion of coal}}$$

Overall efficiency = Thermal efficiency × Electrical efficiency

Problem

Example 2.2. *A thermal station has the following data :*

Max. demand	=	*20,000 kW*	;	*Load factor*	=	*40%*
Boiler efficiency	=	*85%*	;	*Turbine efficiency*	=	*90%*
Coal consumption	=	*0·9 kg/kWh*	;	*Cost of 1 ton of coal*	=	*Rs. 300*

Determine (i) thermal efficiency and (ii) coal bill per annum.

Solution.

(*i*) Thermal efficiency $= \eta_{boiler} \times \eta_{turbine} = 0{\cdot}85 \times {\cdot}9 =$ **0·765 or 76·5 %**

(*ii*) Units generated/annum = Max. demand × L.F. × Hours in a year

$= 20{,}000 \times 0{\cdot}4 \times 8760 = 7008 \times 10^4$ kWh

Coal consumption/annum $= \dfrac{(0\cdot 9)\left(7008 \times 10^4\right)}{1000} = 63{,}072$ tons

∴ Annual coal bill = Rs 300 × 63072 = **Rs 1,89,21,600**

$$\text{Load factor} = \frac{\text{Average load}}{\text{Max. demand}}$$

If the plant is in operation for T hours,

$$\text{Load factor} = \frac{\text{Average load} \times \text{T}}{\text{Max. demand} \times \text{T}} = \frac{\text{Units generated in T hours}}{\text{Max. demand} \times \text{T hours}}$$

Summary

- **Advantages, disadvantages, and operation of thermal power plant**

Hydro-electric Power Station

Hydro-electric Power Station

A generating station which utilizes the potential energy of water at a high level for the generation of electrical energy is known as a hydro-electric power station.

The potential energy stored in a body of water held at a given height is converted to kinetic energy (movement energy) which is used to turn a turbine and produce electricity.

Hydro-electric power stations are generally located in hilly areas where dams can be built conveniently and large water reservoirs can be obtained.

Potential energy → Kinetic energy → Mechanical energy → Electrical energy

Advantages

(i) It requires no fuel as water is used for the generation of electrical energy.

(ii) It is quite neat and clean as no smoke or ash is produced.

(iii) It requires very small running charges because water is the source of energy which is available free of cost.

(iv) It is comparatively simple in construction and requires less maintenance.

Advantages…

(v) It does not require a long starting time like a steam power station. In fact, such plants can be put into service instantly.

(vi) It is robust and has a longer life.

(vii) Such plants serve many purposes. In addition to the generation of electrical energy, they also help in irrigation and controlling floods.

(viii) Although such plants require the attention of highly skilled persons at the time of construction, yet for operation, a few experienced persons may do the job well.

Disadvantages

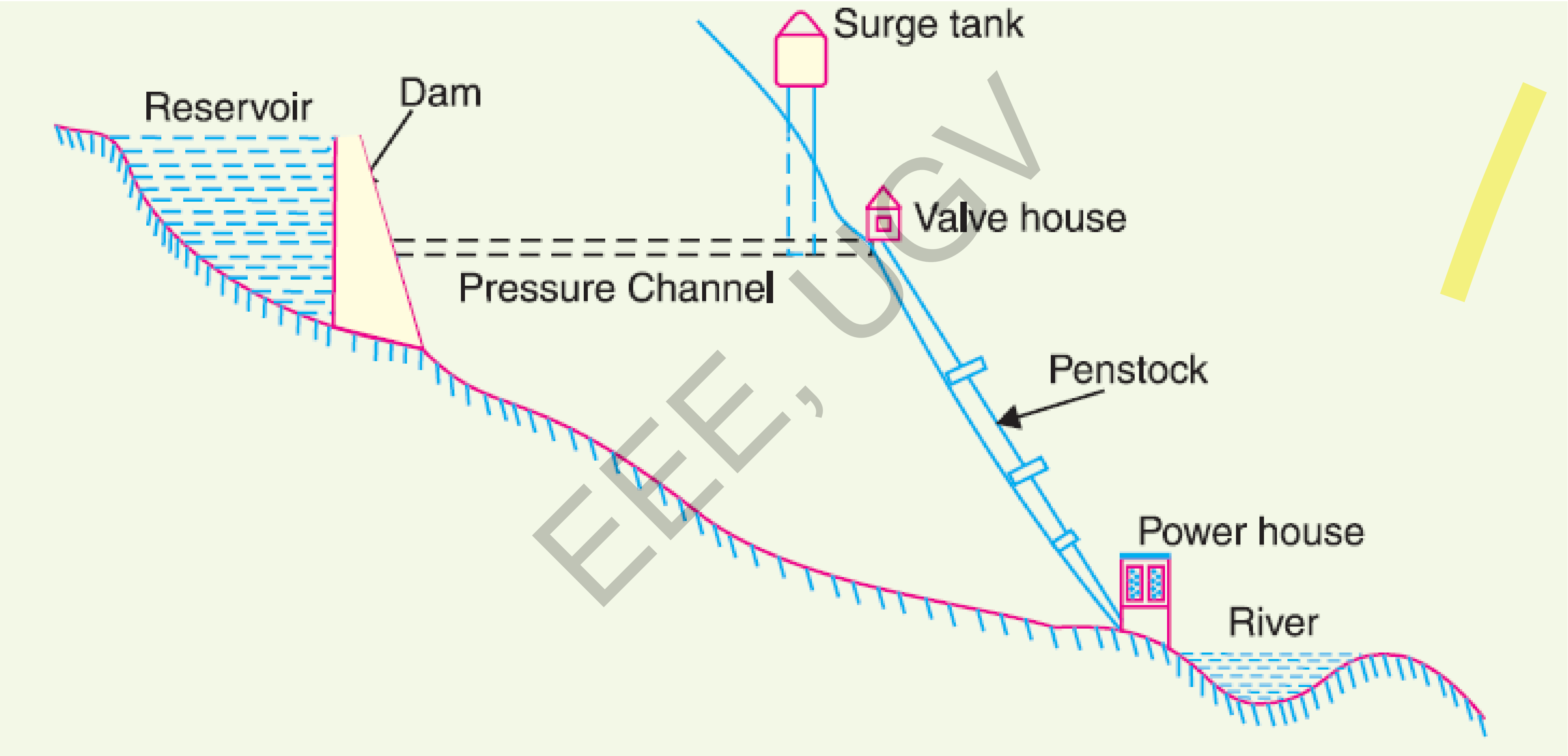
(i) It involves high capital cost due to construction of dam.

(ii) There is uncertainty about the availability of huge amount of water due to dependence on weather conditions.

(iii) Skilled and experienced hands are required to build the plant.

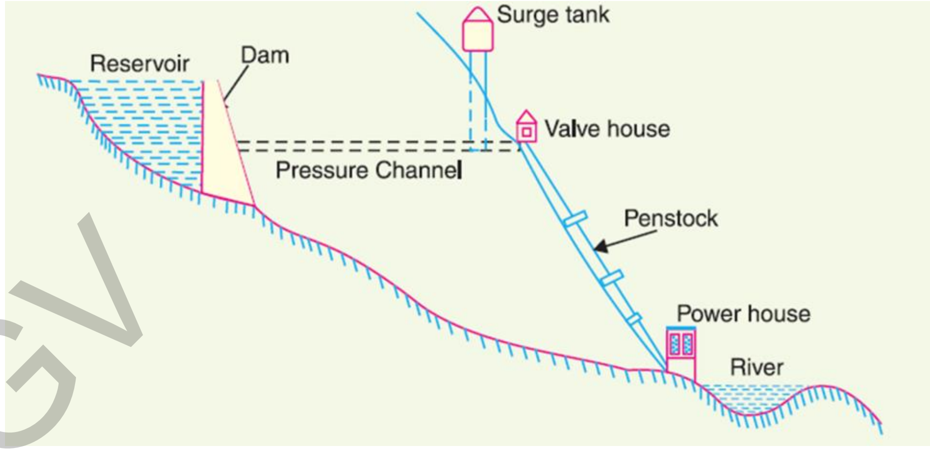
(iv) It requires high cost of transmission lines as the plant is located in hilly areas which are quite away from the consumers.

Schematic Arrangement



Components of Hydro-electric Power Plant

The constituents of a hydro-electric plant are
(1) hydraulic structures
(2) water turbines and
(3) electrical equipment.



- **Dam:** A dam is a barrier which stores water and creates water head. It is a wall built across a river that stops the river's flow and collects the water, especially to make a reservoir.

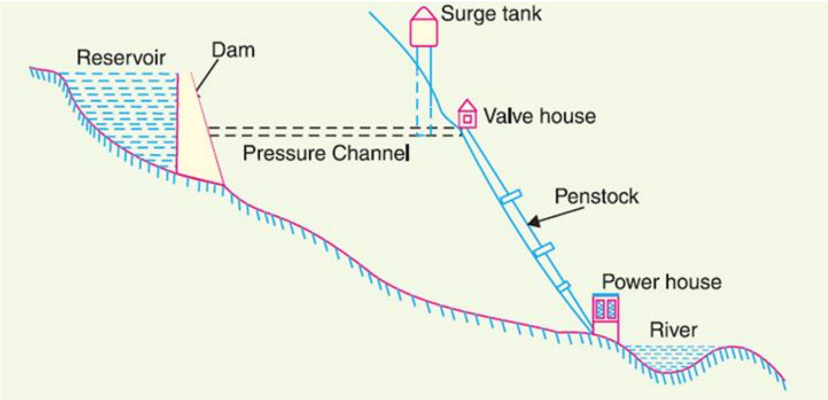
- **Water reservoir:** It stores the water received from the catchment areas during monsoon period. Water surface in the storage reservoir is known as head race.

- **Spillways:** There are times when the river flow exceeds the storage capacity of the reservoir. Such a situation arises during heavy rainfall in the catchment area. In order to discharge the surplus water from the storage reservoir into the river on the down-stream side of the dam, spillways are used.

- **Pressure tunnel/channel:** It carries water from the reservoir to valve house.

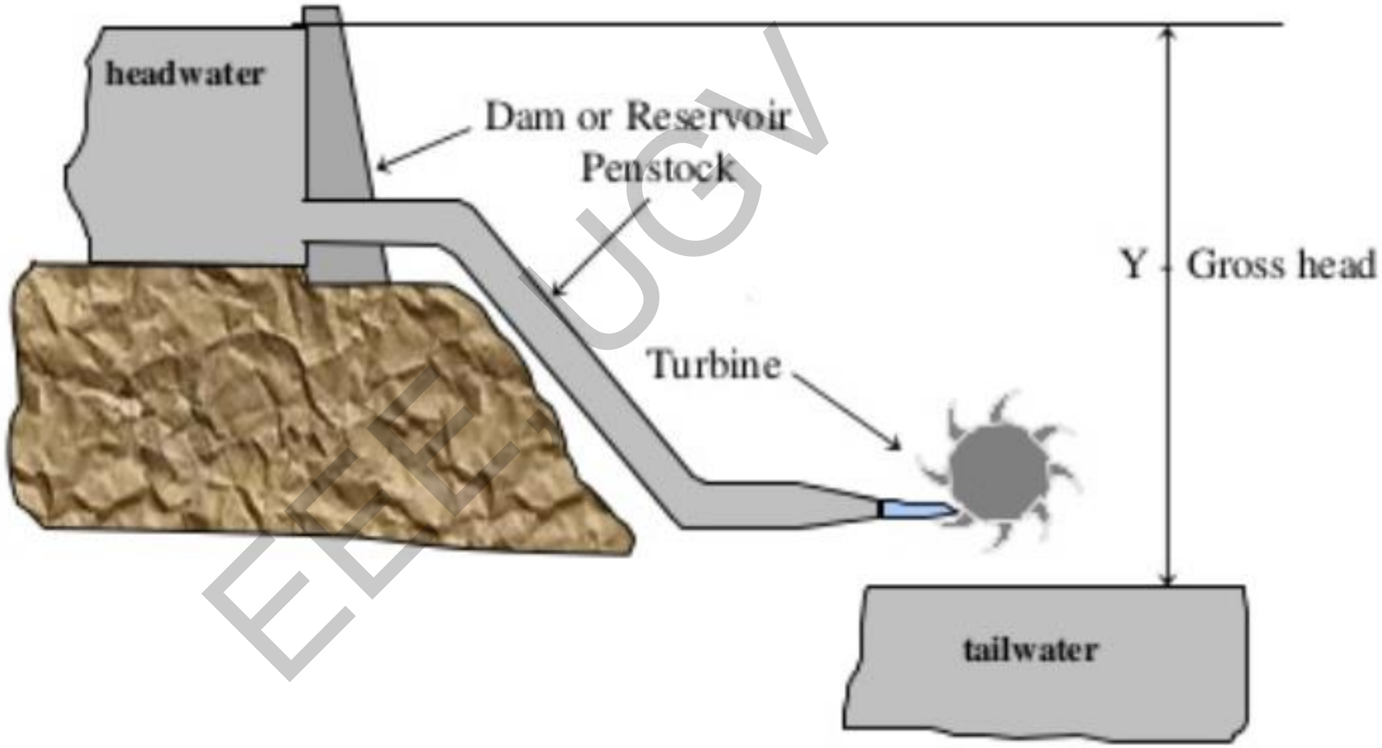
Components of Hydro-electric Power Plant

Surge tank: A surge tank is a small reservoir or tank (open at the top) in which water level rises or falls to reduce the pressure swings in the conduit. A surge tank is located near the beginning of the conduit. It serves the purpose of reducing water hammering in pipes which can cause damage to pipes. When the turbine is running at a steady load, there are no surges in the flow of water through the conduit i.e., the quantity of water flowing in the conduit is just sufficient to meet the turbine requirements. However, when the load on the turbine decreases, the governor closes the gates of turbine, reducing water supply to the turbine. The excess water at the lower end of the conduit rushes back to the surge tank and increases its water level. Thus, the conduit is prevented from bursting. On the other hand, when load on the turbine increases, additional water is drawn from the surge tank to meet the increased load requirement. Hence, a surge tank overcomes the abnormal pressure in the conduit when load on the turbine falls and acts as a reservoir during increase of load on the turbine.



Penstocks: From the valve house, water is taken to water turbine through a huge steel pipe known as penstock.

Water Head


headwater
Dam or Reservoir
Penstock
Turbine
Y
Gross head
tailwater

Site Selection

- **Availability of water**

Since the primary requirement of a hydro-electric power station is the availability of huge quantity of water, such plants should be built at a place (e.g., river, canal) where adequate water is available at a good head.

- **Storage of water**

There are wide variations in water supply from a river or canal during the year. This makes it necessary to store water by constructing a dam in order to ensure the generation of power throughout the year. The storage helps in equalizing the flow of water so that any excess quantity of water at a certain period of the year can be made available during times of very low flow in the river. This leads to the conclusion that site selected for a hydro-electric plant should provide adequate facilities for erecting a dam and storage of water.

Site Selection…

- **Cost and type of land**

The land for the construction of the plant should be available at a reasonable price. Further, the bearing capacity of the ground should be adequate to with-stand the weight of heavy equipment to be installed.

- **Transportation facilities**

The site selected for a hydro-electric plant should be accessible by rail and road so that necessary equipment and machinery could be easily transported.

Expression for Power

The amount of power, and therefore energy that you can generate is proportional to the head and the flow.

$$\text{Available Power, P} = \text{Head} \times \text{Flow} \times \text{Water density} \times \text{Gravitational Constant} \times \text{Efficiency}$$

$$= H \times Q \times \rho \times g \times \eta_{overall} \quad \text{Watt}$$

where,

g is acceleration due to gravity (9.81 m/s^2)
ρ is water density (1000 kg/m^3)
Q is the flow (or) discharge m^3/s
H is the height of fall of water or head in meter

Problem

Example 2.6. *A hydro-electric generating station is supplied from a reservoir of capacity 5×10^6 cubic metres at a head of 200 metres. Find the total energy available in kWh if the overall efficiency is 75%.*

Solution.

Electrical Energy available, $E = m \times g \times H \times \eta_{overall}$

$= 5 \times 10^6 \times 1000 \times 9.81 \times 200 \times 0.75$ **Watt-Sec**

Mass of 1 m^3 of water is 1000 kg

$$= \frac{5\times10^6\times1000\times9.81\times200\times0.75}{3600\times1000}\ kWh$$

$= 2.044 \times 10^6\ kWh$

Summary

- ❖ **Advantages, disadvantages, and operation of hydro-electric power plant**

Non-conventional Sources of Energy

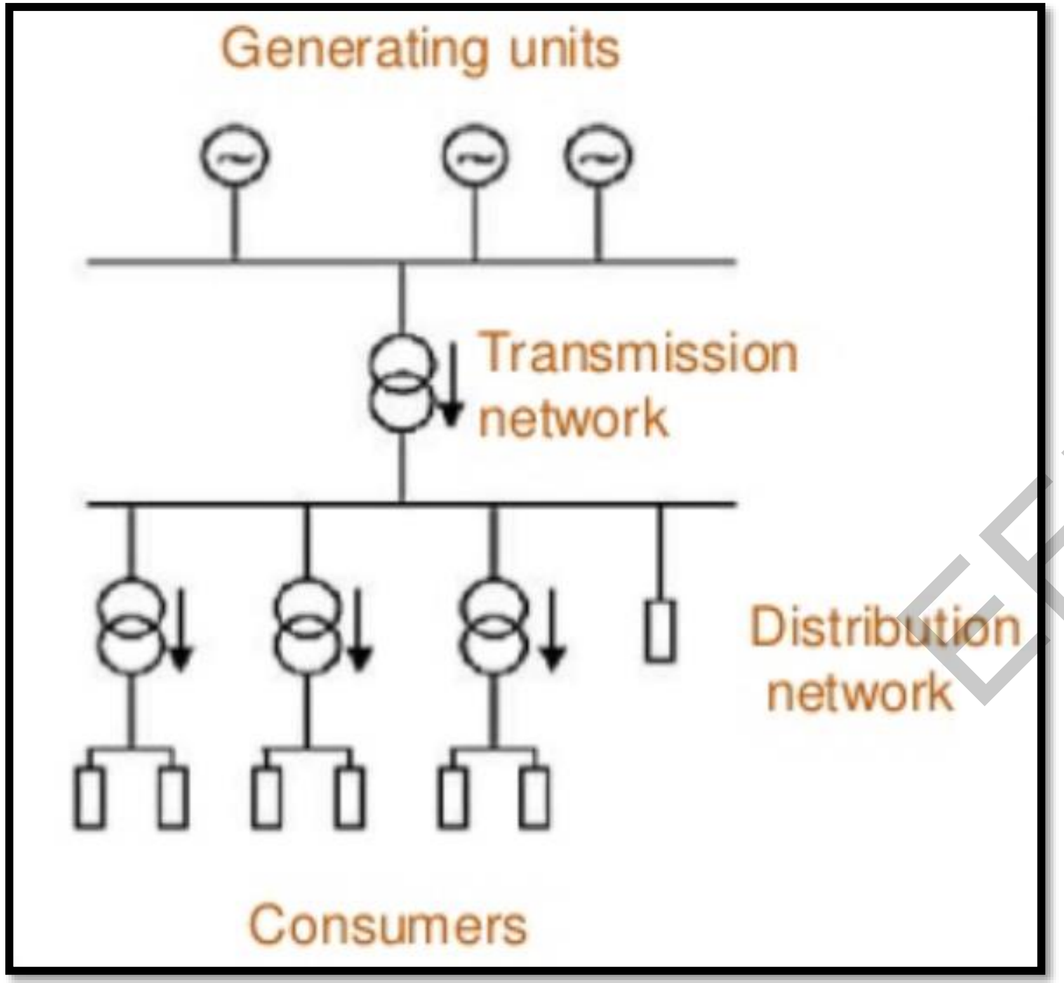
Need for the search of non-conventional sources of energy

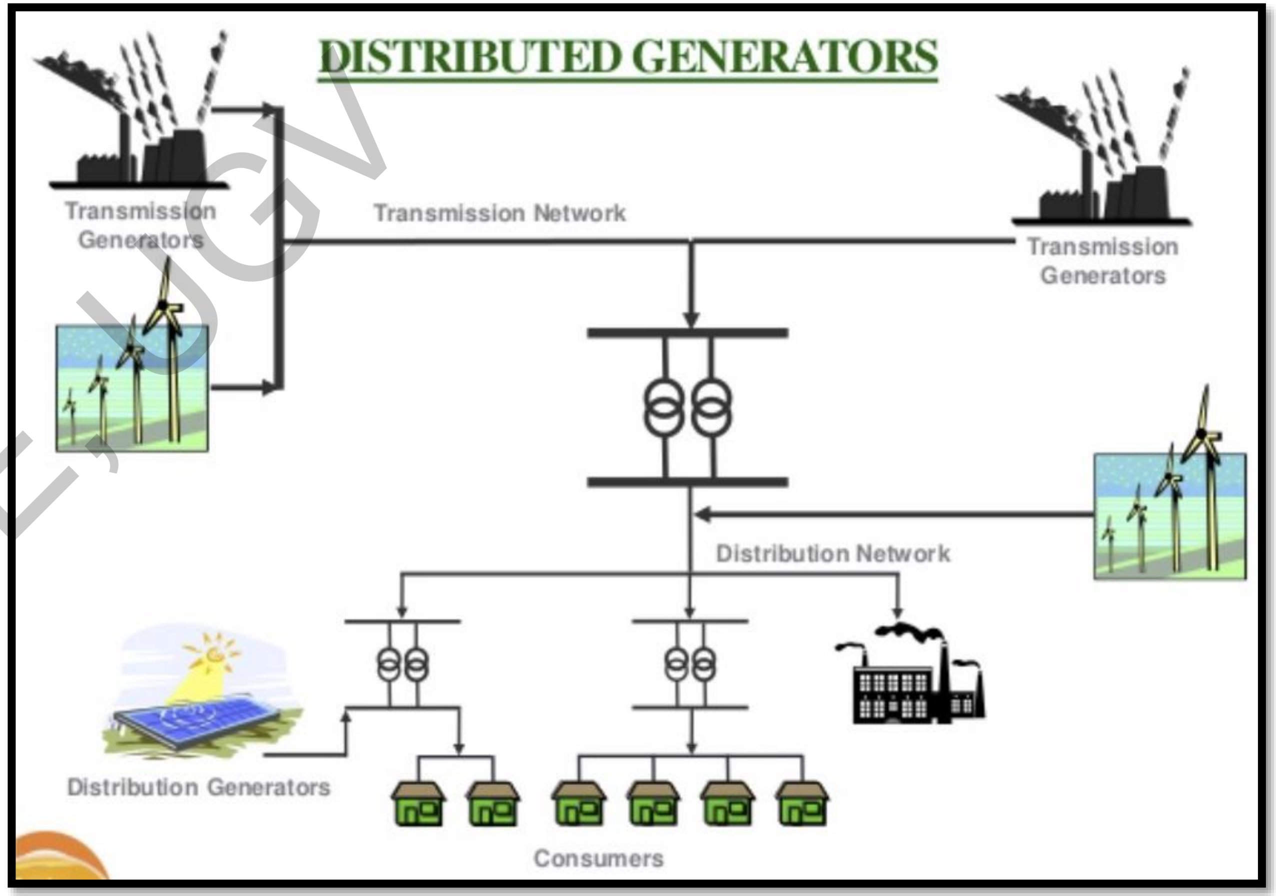
- **The reserve of fossil fuels (coal, oil, natural gas) in the world is depleting very fast and if they are used at the same rate indiscriminately, they will soon be exhausted. Moreover, there are serious pollution hazards like greenhouse effect and global warming which occur due to fossil fuel burning.**

- **It is necessary to find out the various resources and use them economically.**

- **There is an urgent need to find out renewable sources of energy and their conversion into useful power for use of the community.**

Structure of conventional and modern power system





Smart grid - the concept of modernizing the electric grid.

Non-conventional Sources of Energy

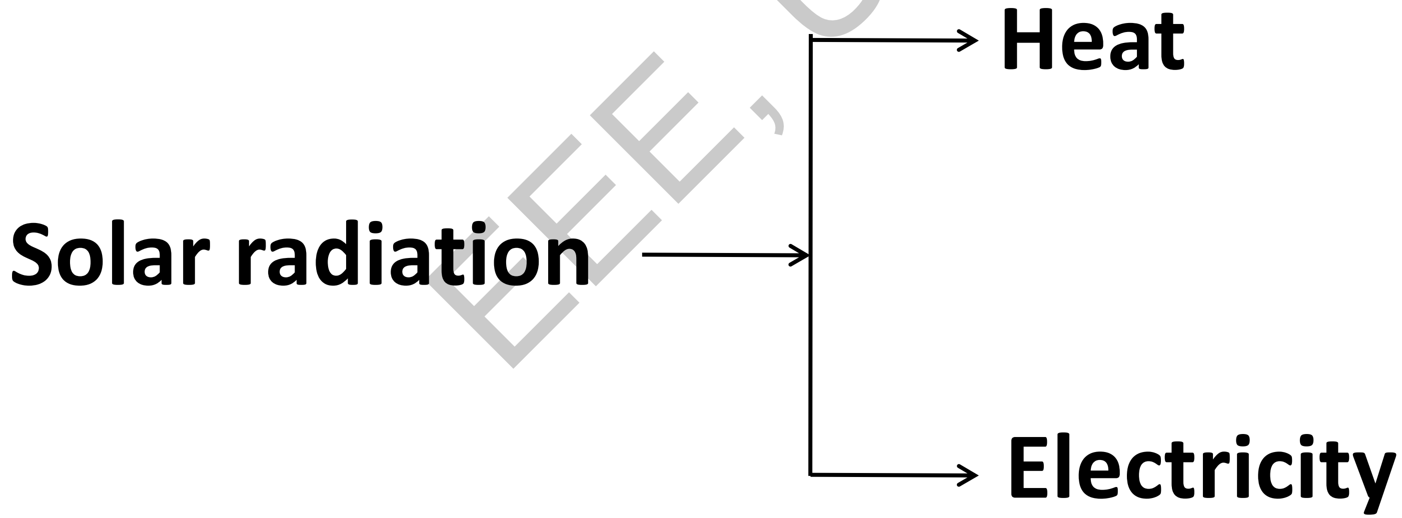
The non-conventional sources of energy used for generating power in lesser magnitude are as follows:

- **Solar energy**
- **Wind energy**
- **Tidal power**
- **Bio-gas**
- **Maneto-hydro-dynamic plant**
- **Geo-thermal energy**
- **Fuel cells**
- **Thermo-electric generation**
- **Thermionic converter**

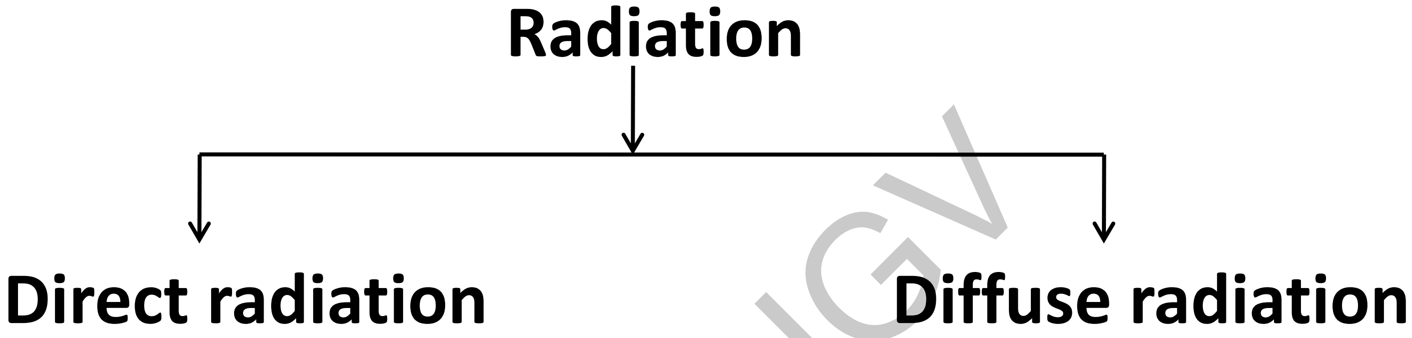
Solar Energy

Solar Energy

The sun's energy is the primary source of energy for life on our planet.



Solar Energy



Direct radiation:

Solar radiation that has not been absorbed or scattered and reaches the ground directly from the sun is called direct radiation.

Diffuse radiation:

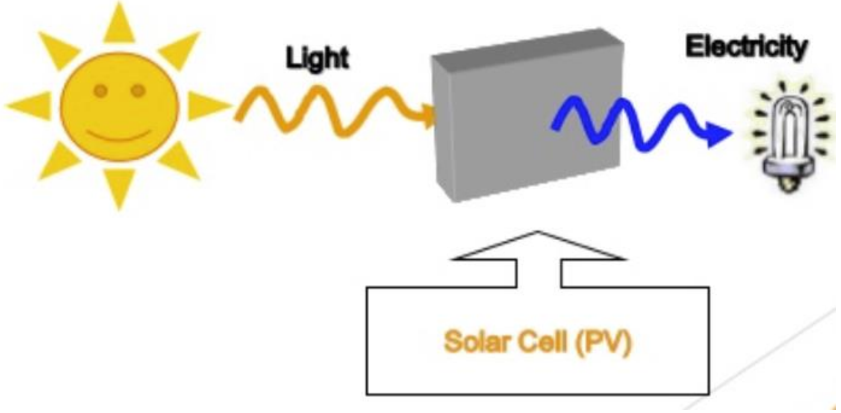
The radiations received after scattering is called diffuse radiation. Diffuse radiation comes to earth from all parts of the sky.

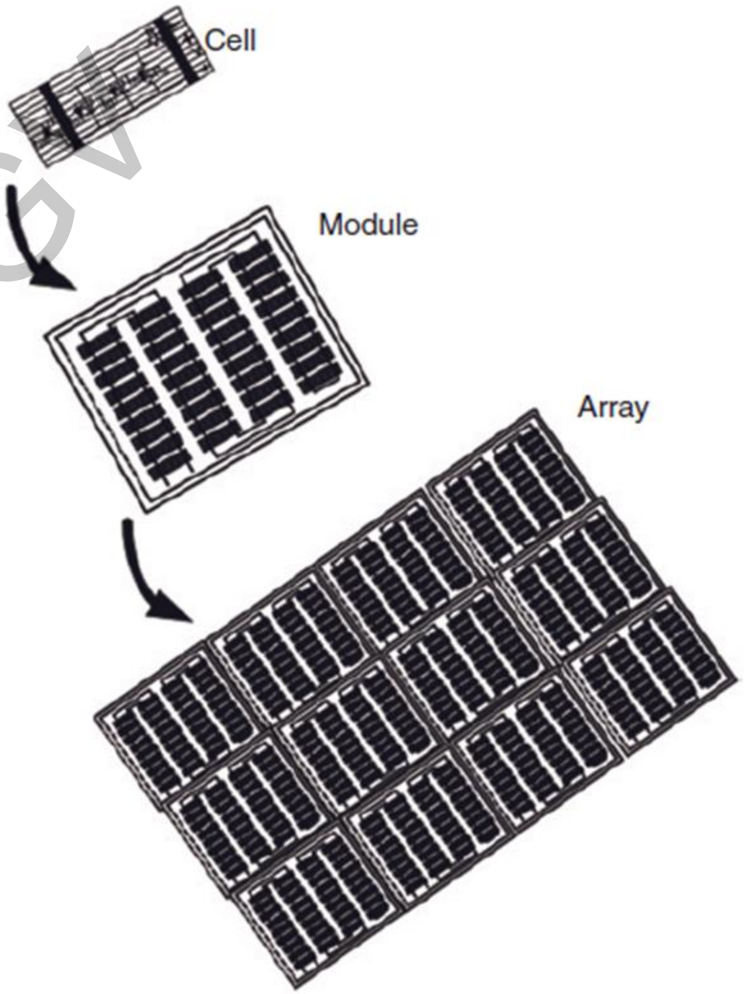
Solar energy…

- **Solar Photovoltaic**

- **Concentrating Solar Power**

Solar energy…





Generation of Electricity -PV

- **Solar PV module is a semiconductor device which converts sunlight directly into dc electricity.**

- **The amount of electricity a solar PV module can generate depends on the amount of sunlight available to it.**

- **The higher the intensity of the sunlight, the more the electricity generated from it.**

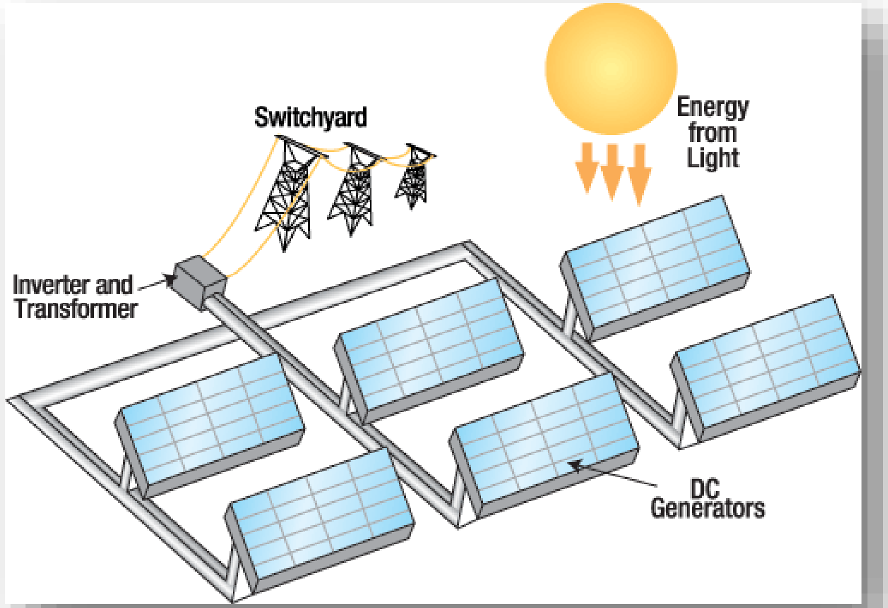
- **When no sunlight falls on a solar PV module, no electricity is generated.**

Generation of Electricity…

- **The amount of electricity generated from a PV module also depends on the size of the module.**
- **The larger the size of the module the higher will be the amount of electricity generated from it.**
- **The electricity generated from a PV module is DC in nature. The conventional supply available to us is AC in nature.**
- **The conversion of DC power to AC power can be achieved using a device called inverter.**

Advantages & Drawbacks…

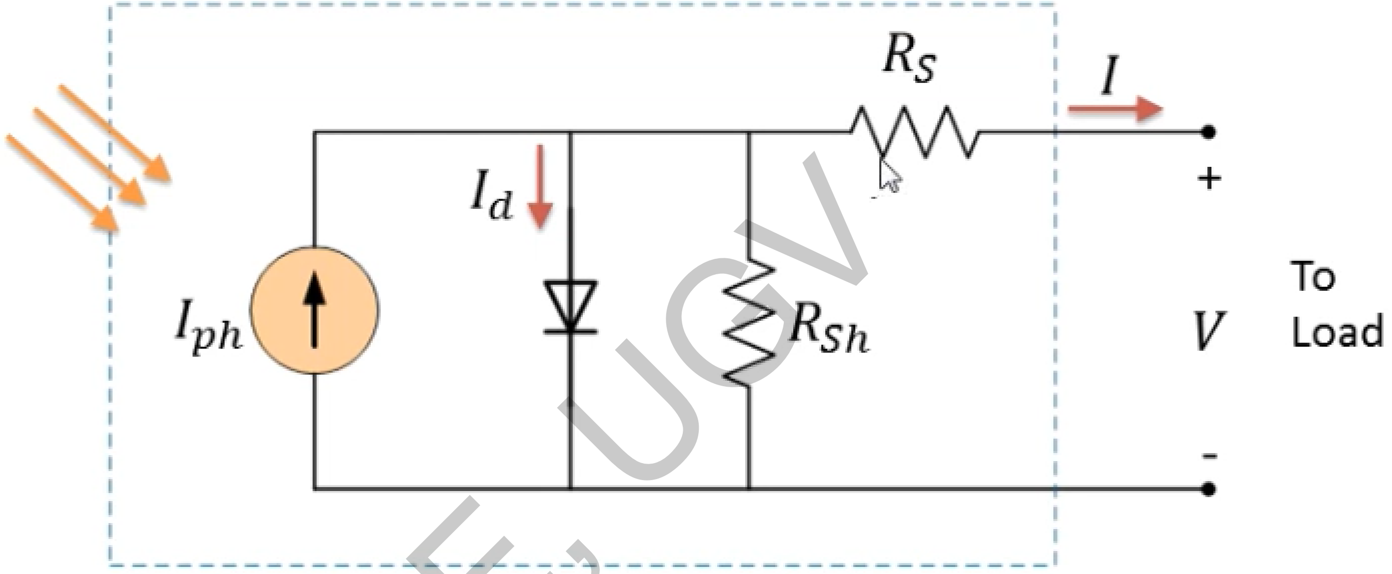
- **Advantages**
  - free of cost
  - non-exhaustible
  - completely pollution-free
  - Devoid of political control



(Source: http://rsindiagroups.com/solar_energy.html)

- **Drawbacks**
  - energy density per unit area is very low
  - available for only a part of the day
  - cloudy and hazy atmospheric conditions greatly reduce the energy received

Approximate equivalent circuit model for a solar cell



$$I = I_{ph} - I_d - I_{R_{sh}}$$

$$I = I_{ph} - I_o\left(e^{\frac{q(V + I R_S)}{akT}} - 1\right) - \left(\frac{V + I R_S}{R_{Sh}}\right)$$

Iph represents current that the solar cell generated by light, Id is the reverse saturation current of solar cells, a is the ideal parameter of solar cells (a = 1~5), *K* is Boltzmann constant (1.3806 × 10−23 J/◦K), *q* is electron charge (1.6×10^{-19} C), and T is reference temperature of solar cells.

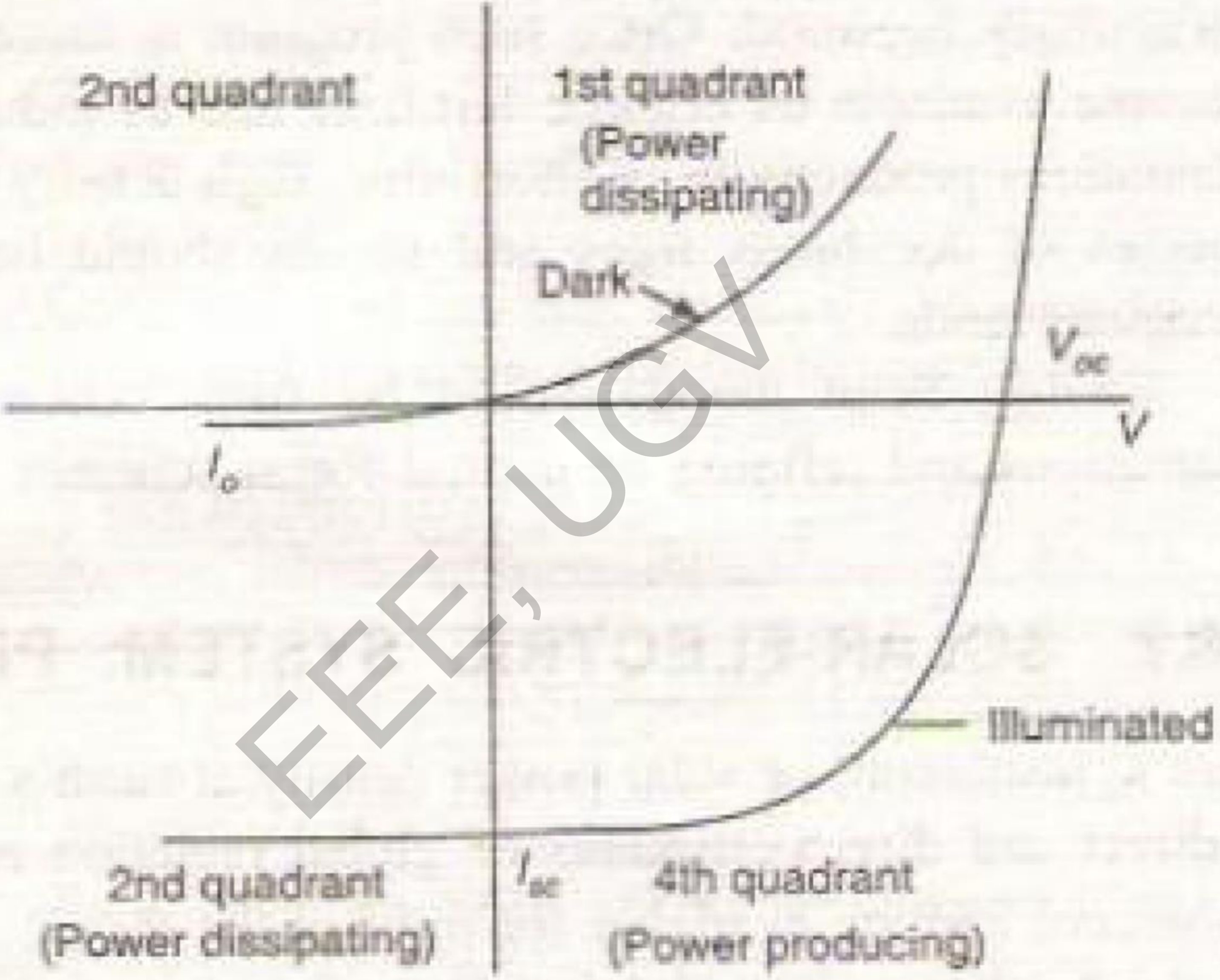
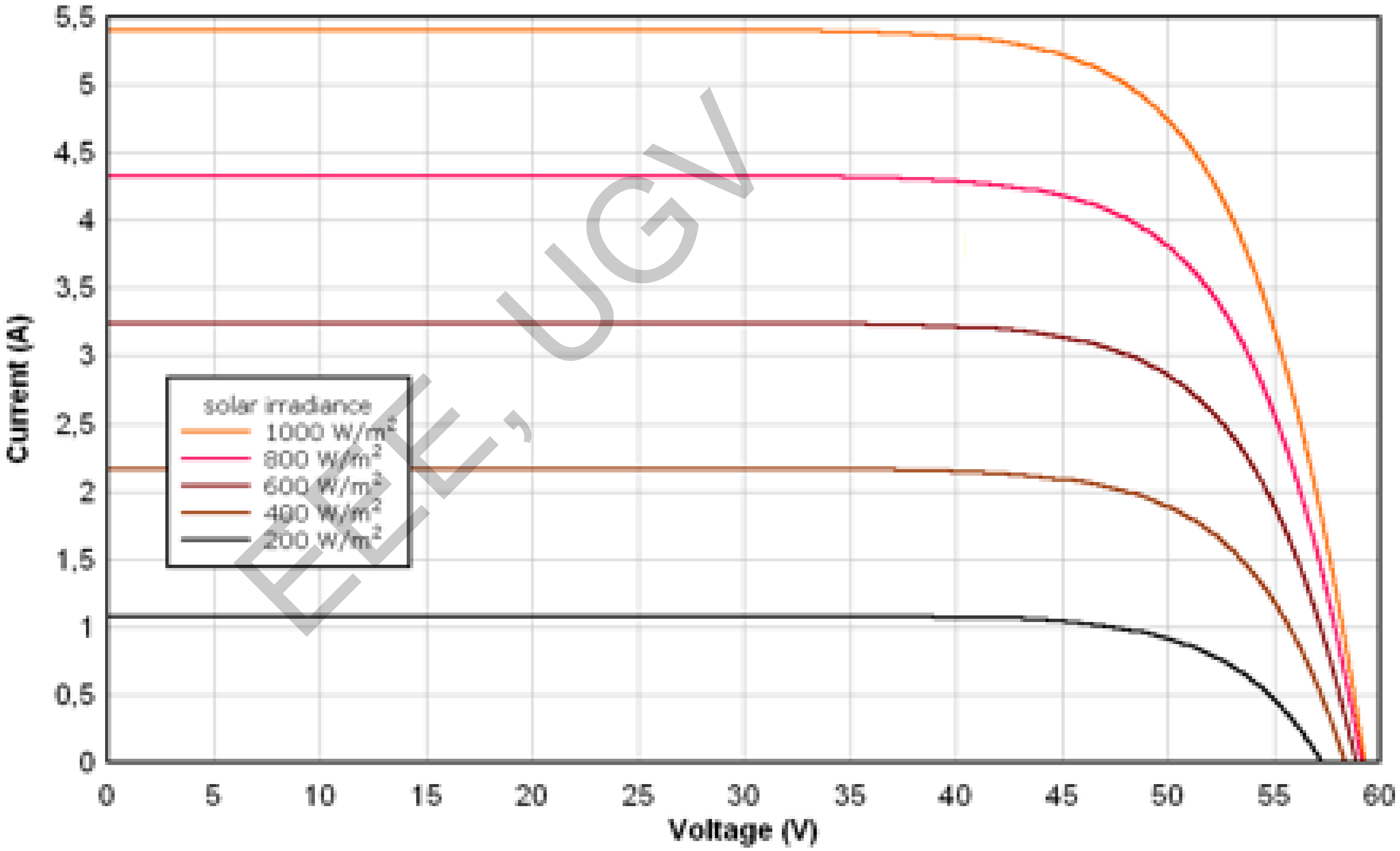


Figure 16.2 *P–N* Junction characteristics of solar cell.

The effects of irradiance on the I-V curve of PV cells

Short-circuit current increases linearly with insolation



I-V characteristics of solar cells at various illumination levels

https://www.pvresources.com/en/solarcells/solarmodules.php

Fill Factor

- **Fill factor is found from the solar cell I-V characteristics or equivalent J-V characteristics.**

Maximum power point - MPP

$$\textbf{Fill Factor (FF)} = \frac{V_{mp} \times J_{mp}}{V_{oc} \times J_{sc}}$$

The fill factor may be 0.8 or higher for well designed solar cell.

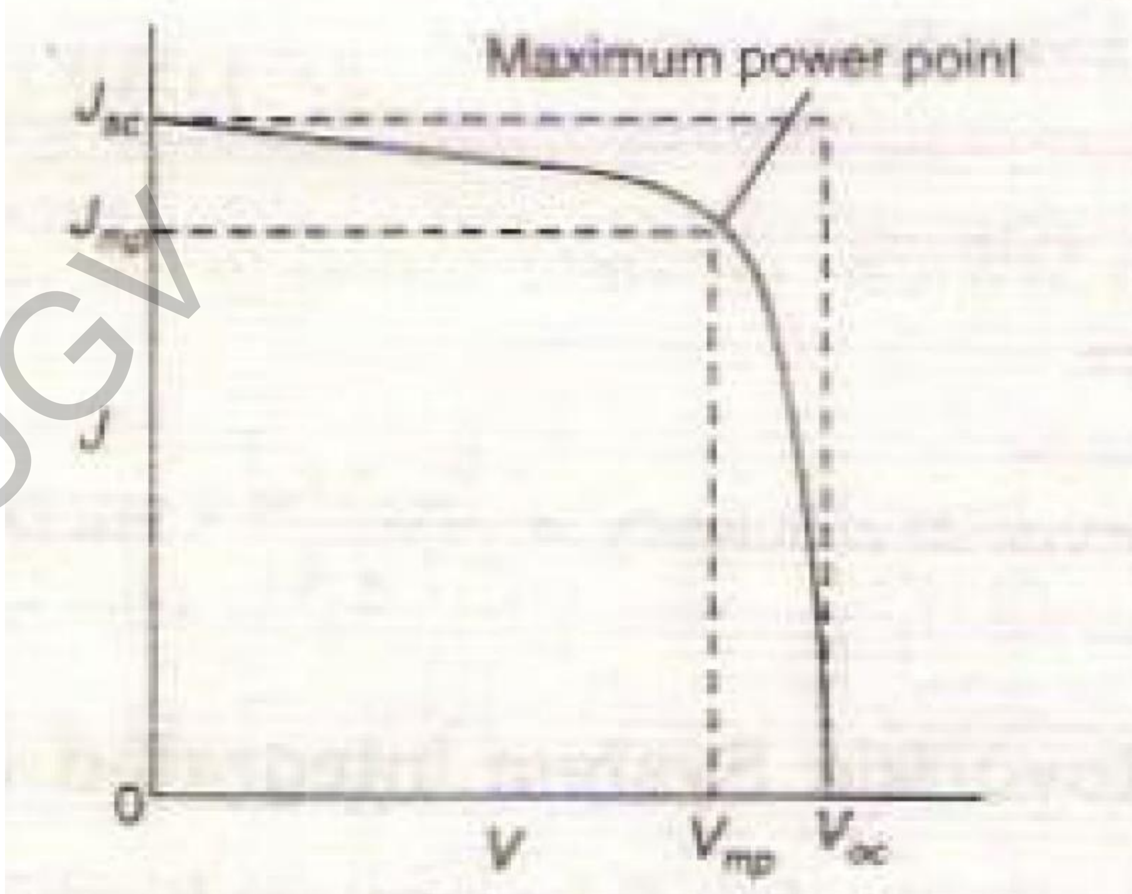


Figure 16.4 Fill factor of a solar cell.

$$FF = \frac{V_{mp} \cdot I_{mp}}{V_{oc} \cdot I_{sc}}$$

$$= \frac{30.18 \times 7.96}{36.72 \times 8.99} = 0.72$$

Conversion efficiency

$$\textbf{Coversion efficiency} = \frac{P_L\,(mW)}{I \times A\,(mW)}$$

$A = \text{Area}(cm^2)$

I=Insolation in (mW/cm^2

$$\textbf{Again, coversion efficiency} = \frac{V_{oc} \times J_{sc} \times Fill\ Factor}{I \times A}$$

Solar Radiation

- **Many factors affect the amount of radiation received at a given location on earth.**
- **These factors include**

  location,

  season,

  humidity,

  temperature,

  air mass, and the hour of day.

Classification-PV

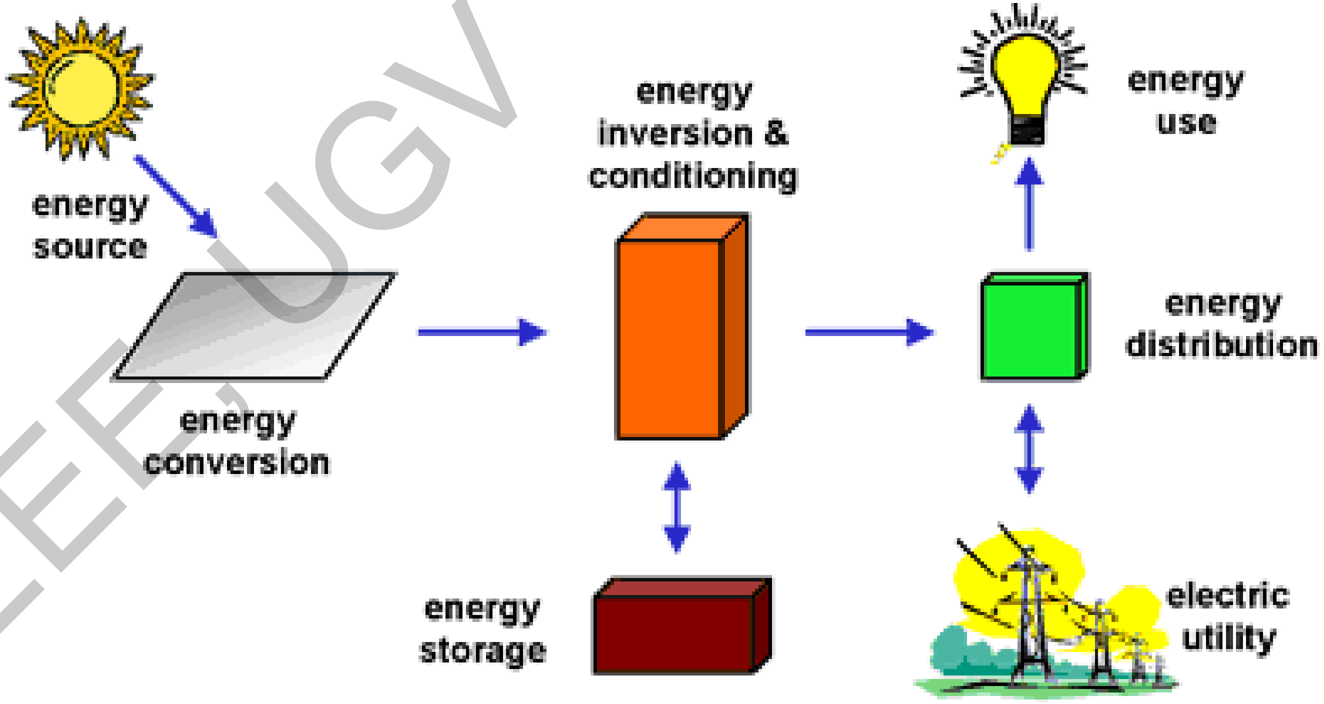
Photovoltaic systems are classified into two major types:

- **off- grid and**
- **grid-connected applications**.

Off-grid PV systems have a significant opportunity for economic application in the un-electrified areas of developing countries, and off-grid PV mini-grid systems have become are liable alternative for village electrification over the last few years.

Classification-PV

- Grid tied PV systems use an inverter to convert electricity from direct current to alternating current, and then supply the generated electricity to the electric grid. Compared to an off-grid installation, system costs are lower because energy storage is not required since the grid is used as a backup.



Grid Integration of PV

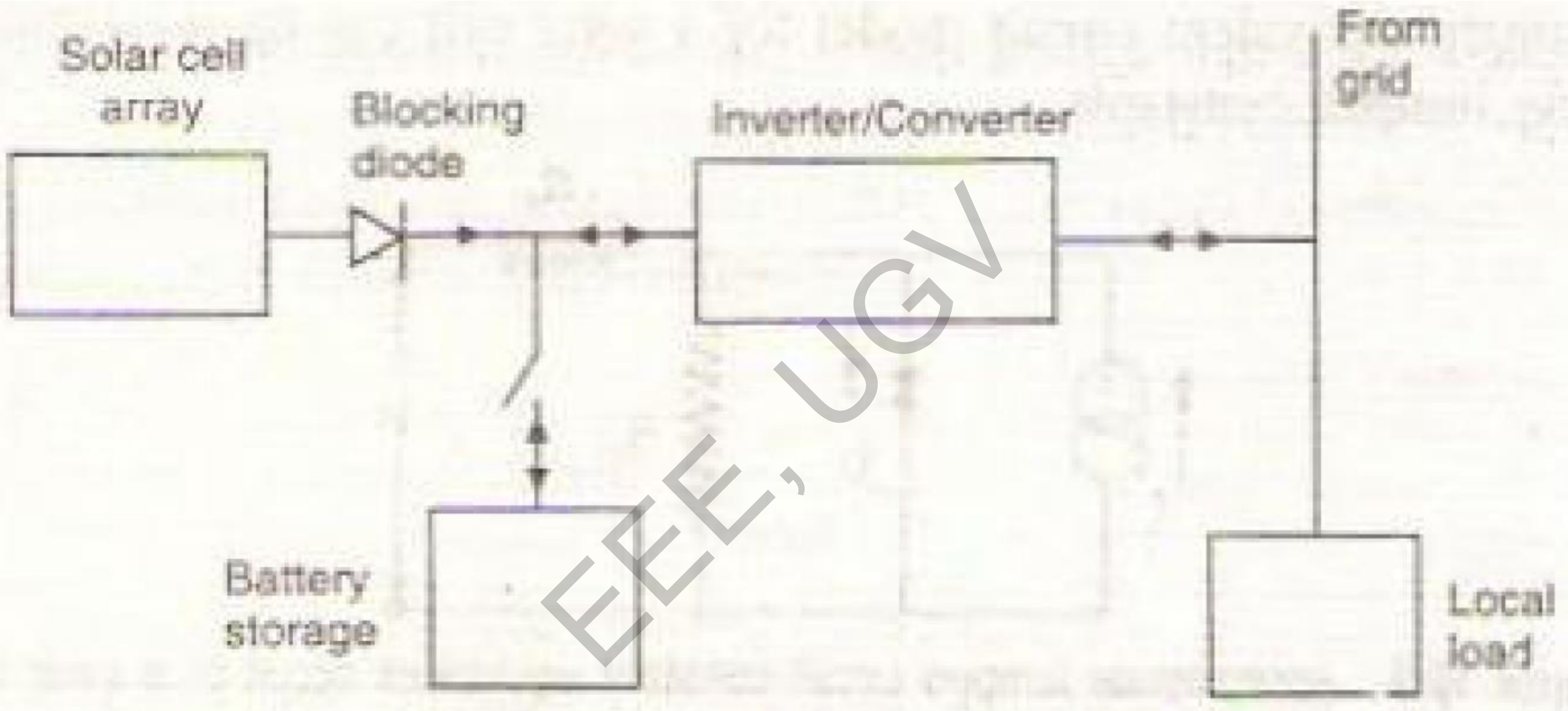


Figure 16.6 Photovoltaic system integrated with power grid.

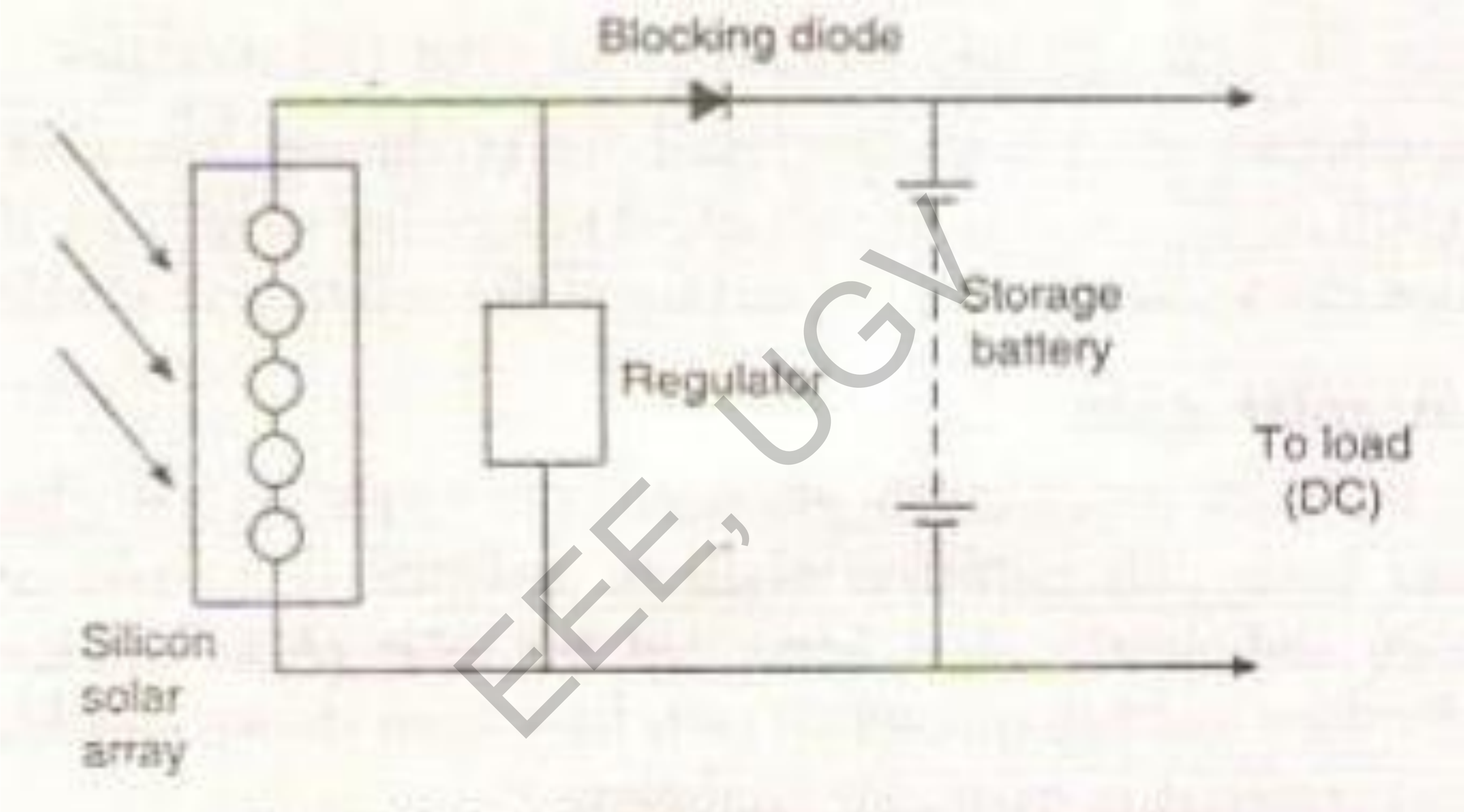
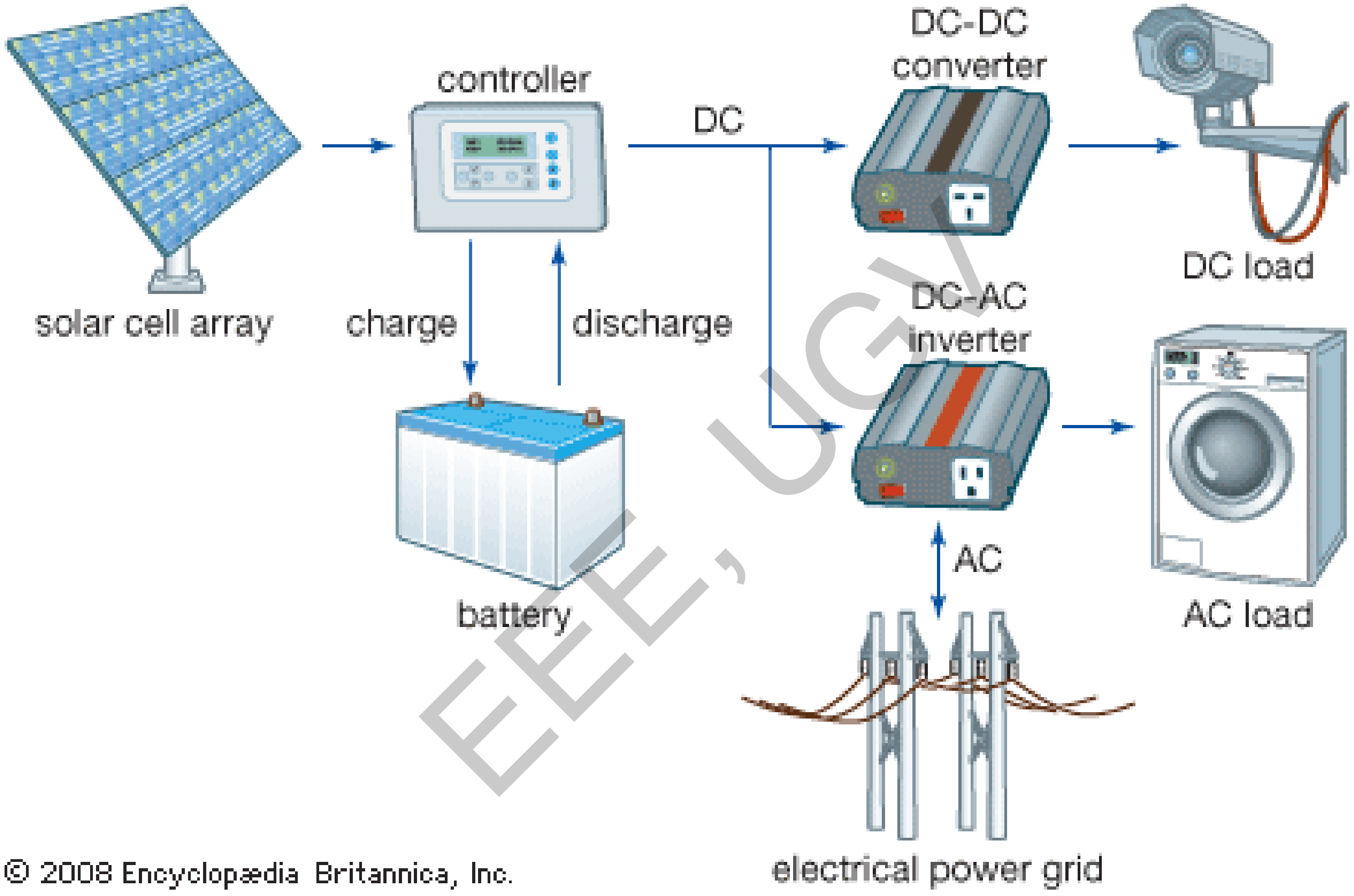
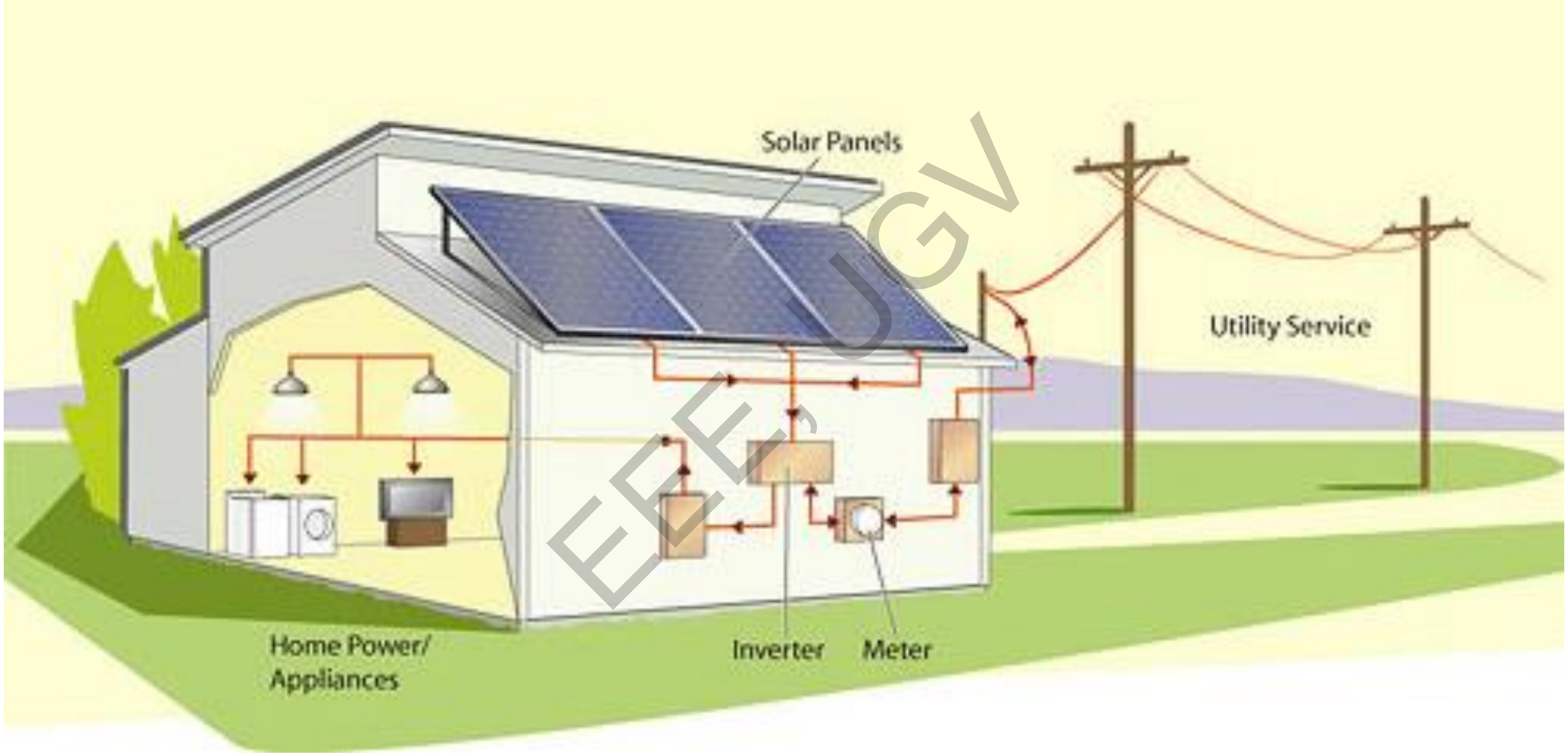


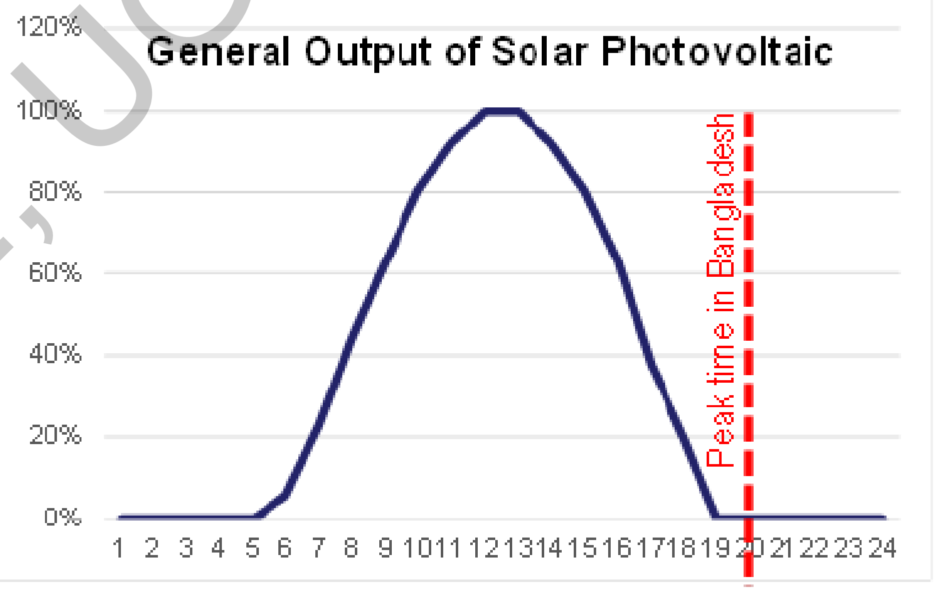
Figure 16.8 Stand alone solar power system.


solar cell array
controller
DC
DC-DC converter
DC load
charge
discharge
DC-AC inverter
AC load
battery
AC
electrical power grid


Solar Panels
Utility Service
Home Power/
Appliances
Inverter
Meter

Barrier

Solar PV technology has low energy-intensity and requires large land area.

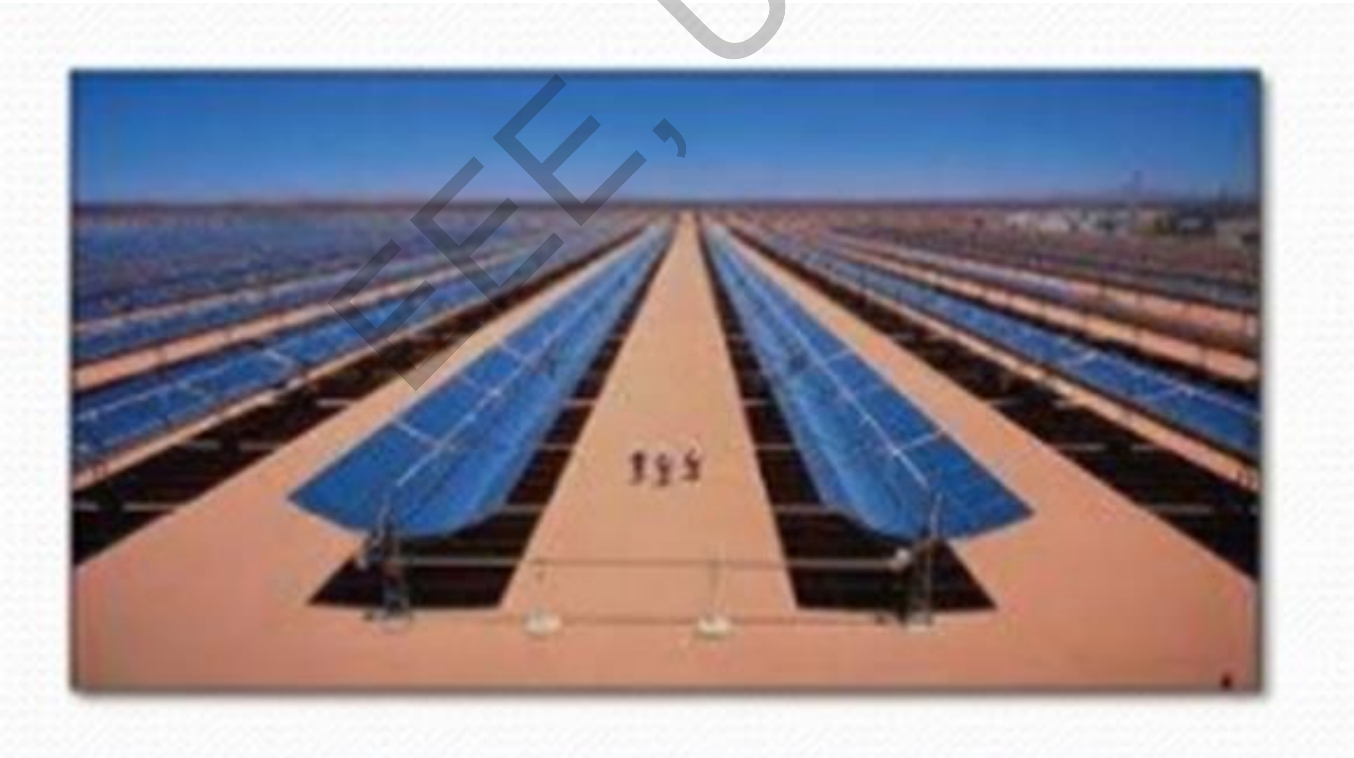


Land availability

We do not know how to store electrical energy on a massive scale

Concentrating solar power

- **CSP technologies can be used to generate electricity by converting energy from sunlight to power a turbine.**
- **It uses solar energy for heating fluids which can be used as a heat source to produce steam from water to drive turbines for generating electricity.**



Applications

- **Water pumping for irrigation and drinking water supply**
- **Community and street lighting**
- **Power supply for micro-wave repeater station**
- **Communication equipment, radio and television receivers**
- **Solar water heaters**
- **Solar refrigeration**
- **Rail road crossing signals, etc.**

Summary

- Need for non-conventional energy sources
- Solar energy technology
- Advantages, disadvantages and application of solar PV

Wind Energy

Introduction

- **Energy of wind can be used for the generation of electrical energy.**

- **The potential of wind energy as a source of power is large.**

- **A wind turbine drives a generator to produce electricity.**

Advantages

- **Non-polluting**
- **Free source of energy**
- **Wind farms are relatively inexpensive**
- **The land of the wind farms can be used for other purposes**
- **Avoid fuel provision and transport**

Disadvantages

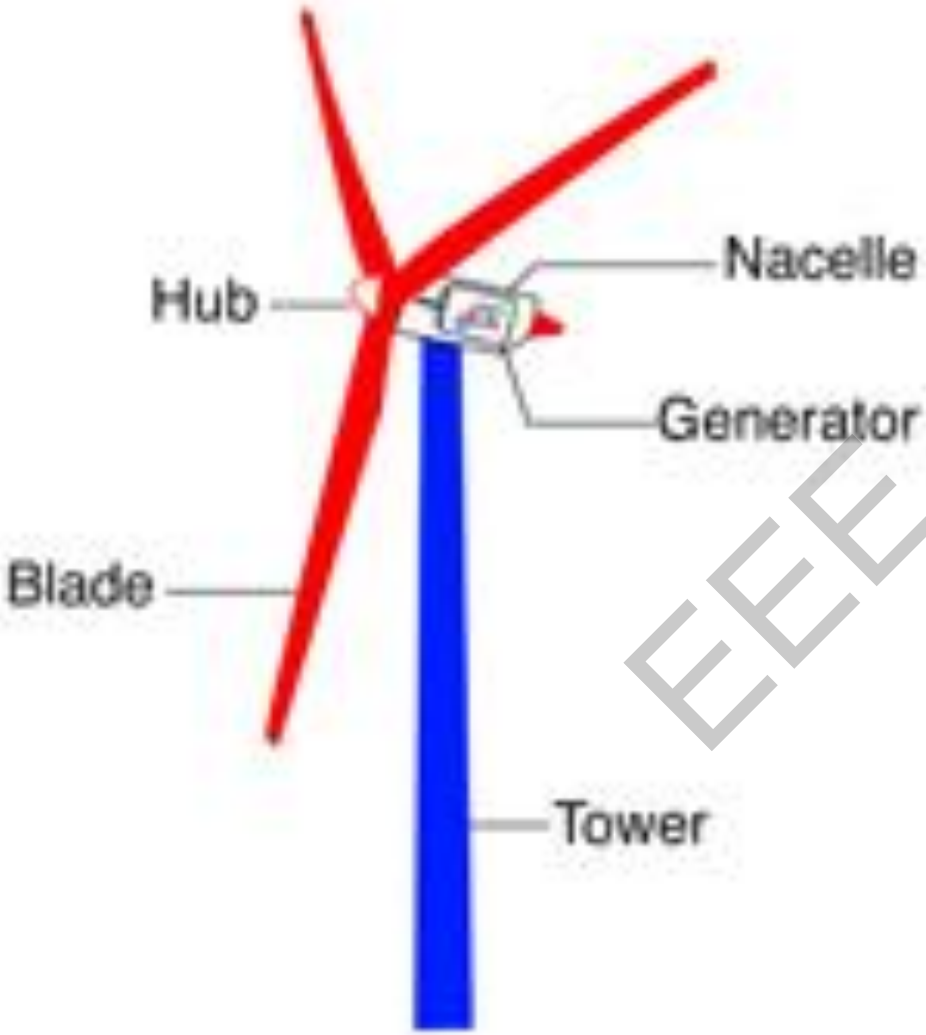
- **Requires steady and significant amount of air**
- **Requires significant amount of space**
- **Have visual impact on landscape**
- **Generates noise**
- **Because of its irregularity it needs storage devices**

Wind Power Project in Bangladesh

SL.	Project Name	SID	Capacity	Location	RE Technology	Agency	Finance	Completion Date	Present Status
1	1000 kW Capacity Wind Battery Hybrid Power Plant	172	1 MW	Kutubdia Upazila, Cox's Bazar	Wind (Off-Grid)	BPDB	Self	2015-12-31	Completed & Running
2	1000 kW Capacity Wind Battery Hybrid Power Plant	171	1 MW	Kutubdia Upazila, Cox's Bazar	Wind (Off-Grid)	BPDB	Self	2008-12-31	Completed & Running
3	Feni Wind Power Plant	173	900 kW	Sonagazi, Feni	Wind (On-Grid)	BPDB	Self	2006-09-27	Completed & Running
4	Design, Supply, Installation, Testing and Commissioning of 2 MW Capacity Wind Power Plant on turnkey basis at the bank of the River Jamuna adjacent to the existing Sirajganj 150 MW Power Plant , Sirajganj, Bangladesh	370	2 MW	Sirajganj Sadar Upazila, Sirajgonj	Wind (On-Grid)	BPDB	Self	2019-01-14	Implementation Ongoing
5	10 MW Wind Power Plant	155	10 MW	Kalapara Upazila, Patuakhali	Wind (On-Grid)	RPCL	GoB	2022-12-31	Under Planning
6	Feasibility Study for Installation of Wind Firm in Matarbari Island	280	0 kW	Maheshkhali Upazila, Cox's Bazar	Wind (On-Grid)	CPGCBL	GoB	2019-06-30	Under Planning
7	"60 MW Wind Power Project" at Cox's Bazar by US-DK Green Energy (BD) Ltd	158	60 MW	Chakaria Upazila, Cox's Bazar	Wind (On-Grid)	BPDB	IPP (Unsolicited)	2017-11-30	Under Planning

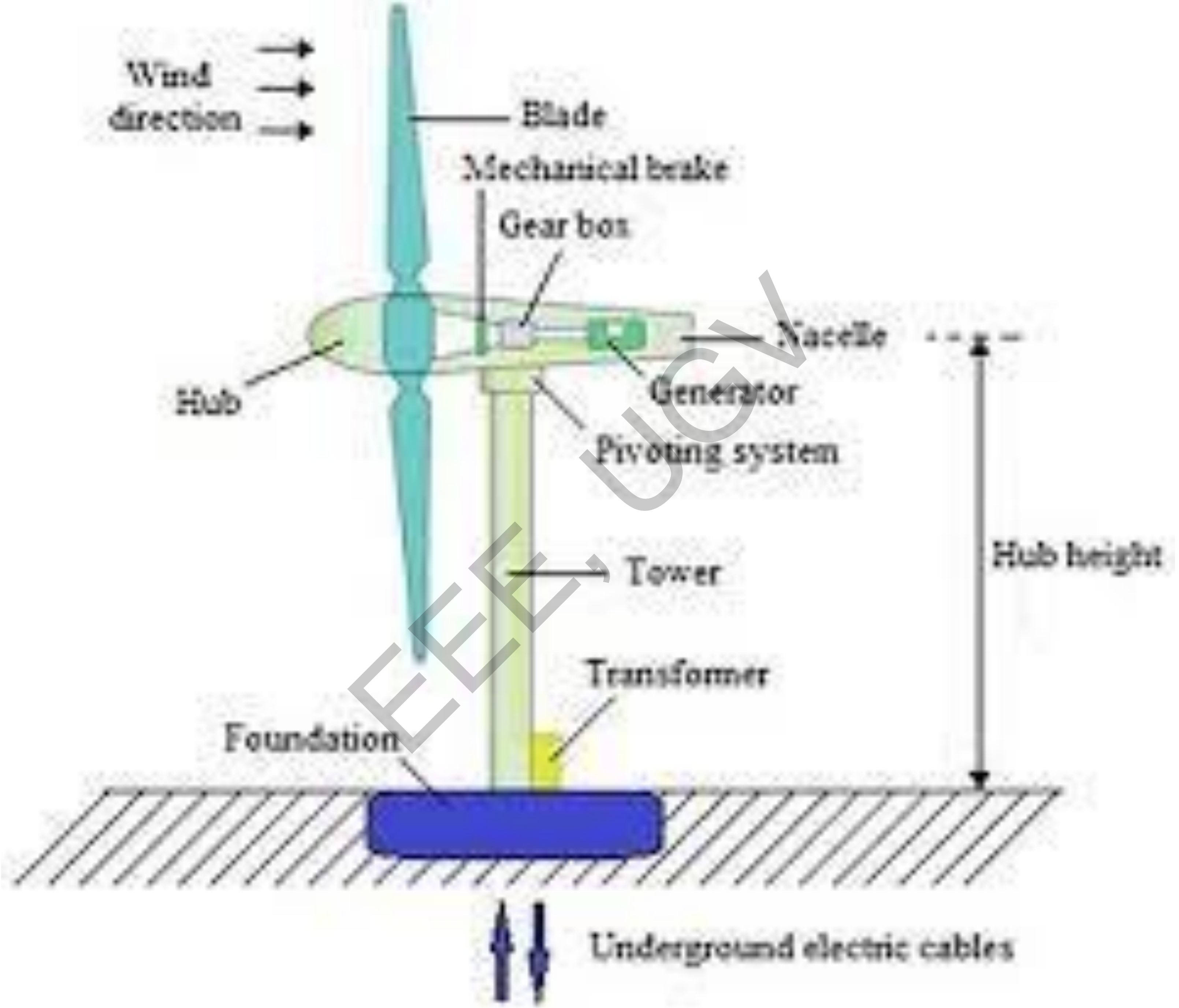
https://ndre.sreda.gov.bd/index.php?id=1&i=11

Components of a WindTurbine



- Hub-The hub is a component of a wind turbine that blades attach to. The hub transfers motion to the generator inside of the nacelle.
- Nacelle-The nacelle is the section of the windturbine that houses the generator.
- Blade-Blades spin from the wind and star the generator. Modern turbines have three blades.
- Tower -The tower is the base section of the wind turbine that the nacelle mounts on to.
- Generator -The generator converts the energy from the wind blades into electricity.

https://www.appropedia.org/w/images/0/04/Handout1s.jpg


Wind
direction
Blade
Mechanical brake
Gear box
Nacelle
Hub
Generator
Pivoting system
Hub height
Tower
Transformer
Foundation
Underground electric cables

Available Wind Power

Wind energy conversion devices are commonly known as wind turbine, because they convert the energy of the wind stream into energy of rotation: the component which rotates is called rotor.

The fraction of free flow wind power than can be extracted by a rotor is called the power coefficient.

K = Power coefficient

$= P_1/P_2$

where P_1 = Power of wind rotor

P_2 = Power available in the wind.

The maximum theoretical power coefficient is 0.593 (Betz Limit)

The mass of air is calculated as follows :

Q = Amount of air passing in unit time

$= A \times V$

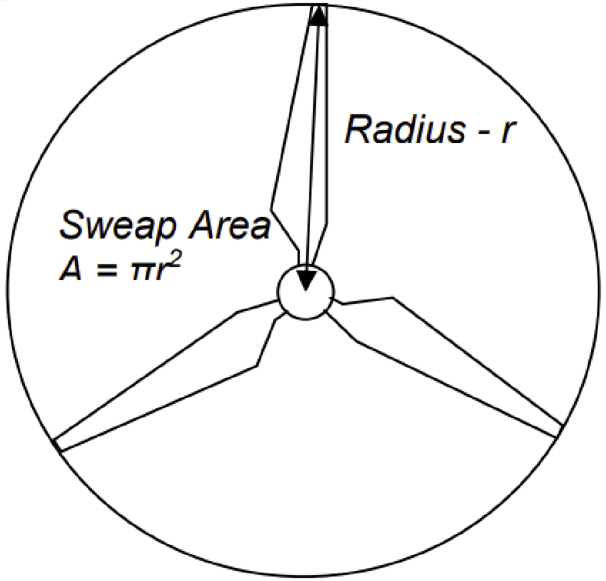
where A = Area through which air passes

V = Velocity of air

M = Mass of air traversing through area A swept by the rotating blades of wind mill type generator.

$$M = \rho \, . \, A \, . \, V$$

where ρ = Density of air



K.E. = Kinetic energy of moving air

$$= \frac{1}{2} M.V^2$$

$$= \frac{1}{2} \rho.A.V.V^2 = \frac{1}{2} \rho.A.V^3$$

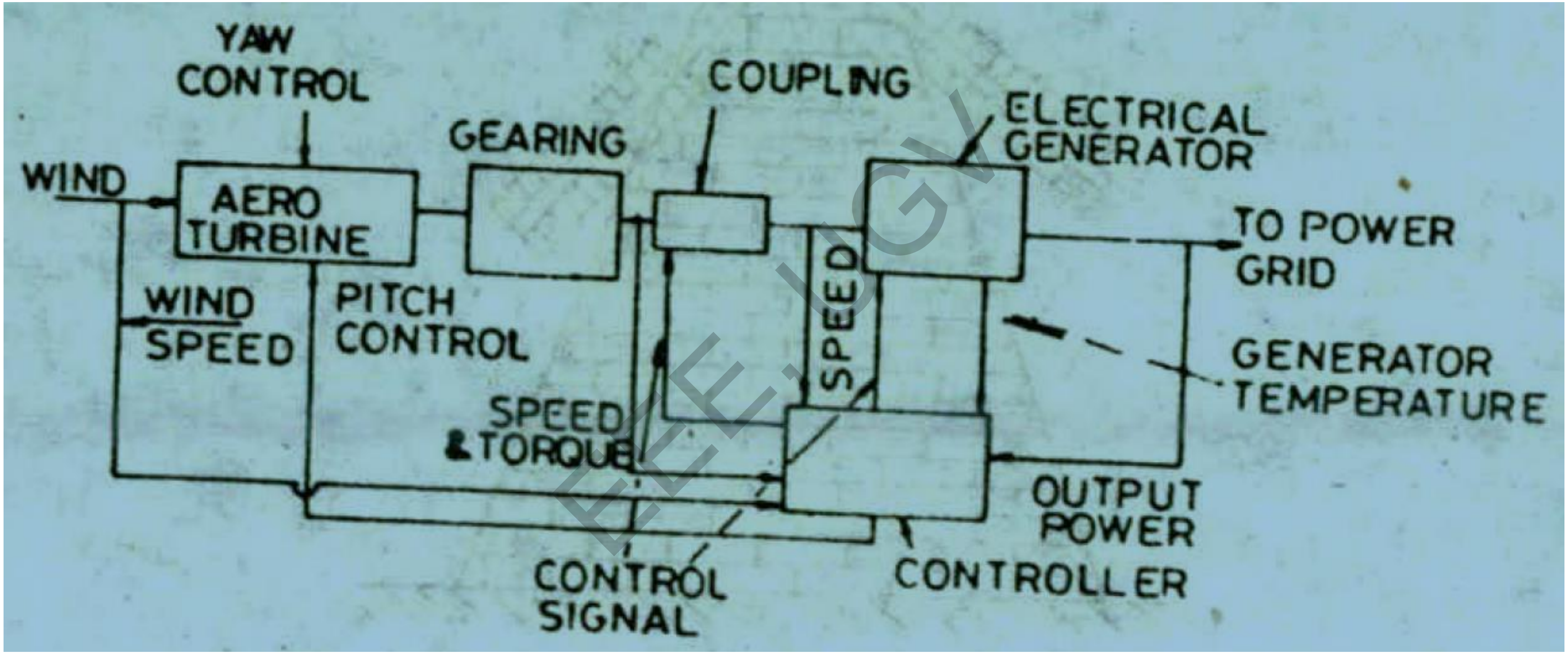
P_2 = Available wind power

= Kinetic energy

$$= \frac{1}{2} \rho.A.V^3$$

The power available in the wind increases rapidly with the speed and hence Wind Energy Conversion (WEC) machines should be located preferably in areas where winds are strong and persistent.

Basic components



Basic Components of a Wind Energy Conversion System (WECS)

Basic components…

- **Aero-turbines convert the wind energy to rotary mechanical energy.**
- **A mechanical interface consisting of a step up gear and a coupling transmits the rotary mechanical energy to an electrical generator.**
- **The output of generator is connected either to the load or power grid.**
- **The purpose of controller is to sense wind speed, wind direction, shafts speeds and torques, output power and generator temperature and make the necessary adjustments.**

Site Selection

- **Wind farms should be installed at sites where winds are strong and persistent. The most suitable sites for wind turbines would be found where the annual average wind speeds are known to be moderately high.**
- **It is desirable to install WECS at higher altitudes because the winds tend to have higher velocities at higher altitudes.**
- **The ground conditions at the site should be such that the foundations for WECS are secured. The land cost should be low.**

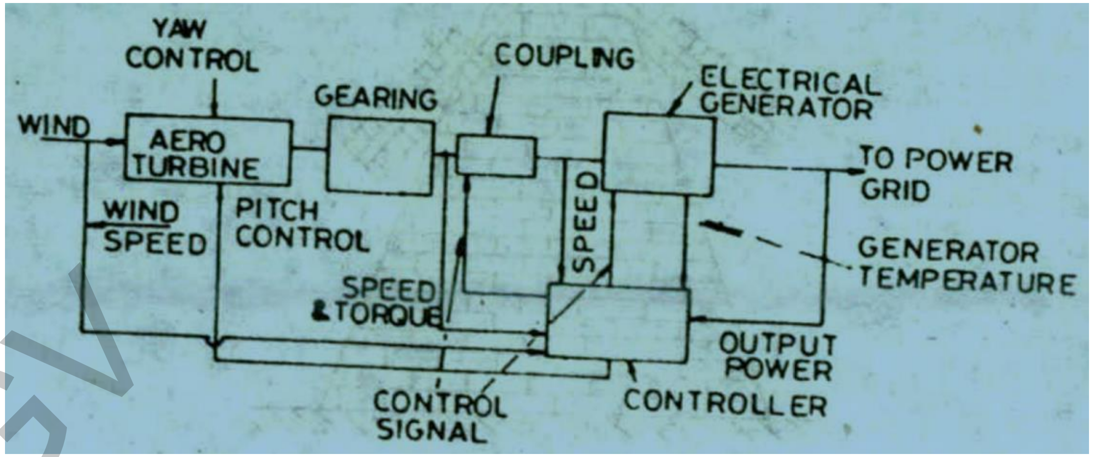
Site Selection...

- **Icing problem, salt spray or blowing dust** should not be present at the site as they affect aeroturbine blades.
- **The site selected should be near to the users of generated electric energy.**
- **The site should be near to the road or railway facilities.**

The best site for wind energy systems are found off-shore and the sea coast and at mountains.

https://www.windpowerengineering.com/detecting-ice-on-wind-turbine-blades/

Efficiency



- Overall efficiency of an aero-generator is

$$n_o = n_A n_g n_c n_{gen}$$

where η_0 = overall conversion efficiency of an aero-generator.

η_g = Efficiency of gearing

η_c = Efficiency of coupling

η_{Gen} = Efficiency of generator

η_A = Efficiency of aeroturbine

Applications

- **Cooling of homes**
- **Space heating**
- **Irrigation**
- **Navigational signals**
- **Offshore drilling operations, etc.**

Summary

- Wind turbine components

- Advantages, disadvantages and applications of wind energy.

Magneto Hydro Dynamic (MHD) Generator

Magneto Hydro Dynamic (MHD) Generator

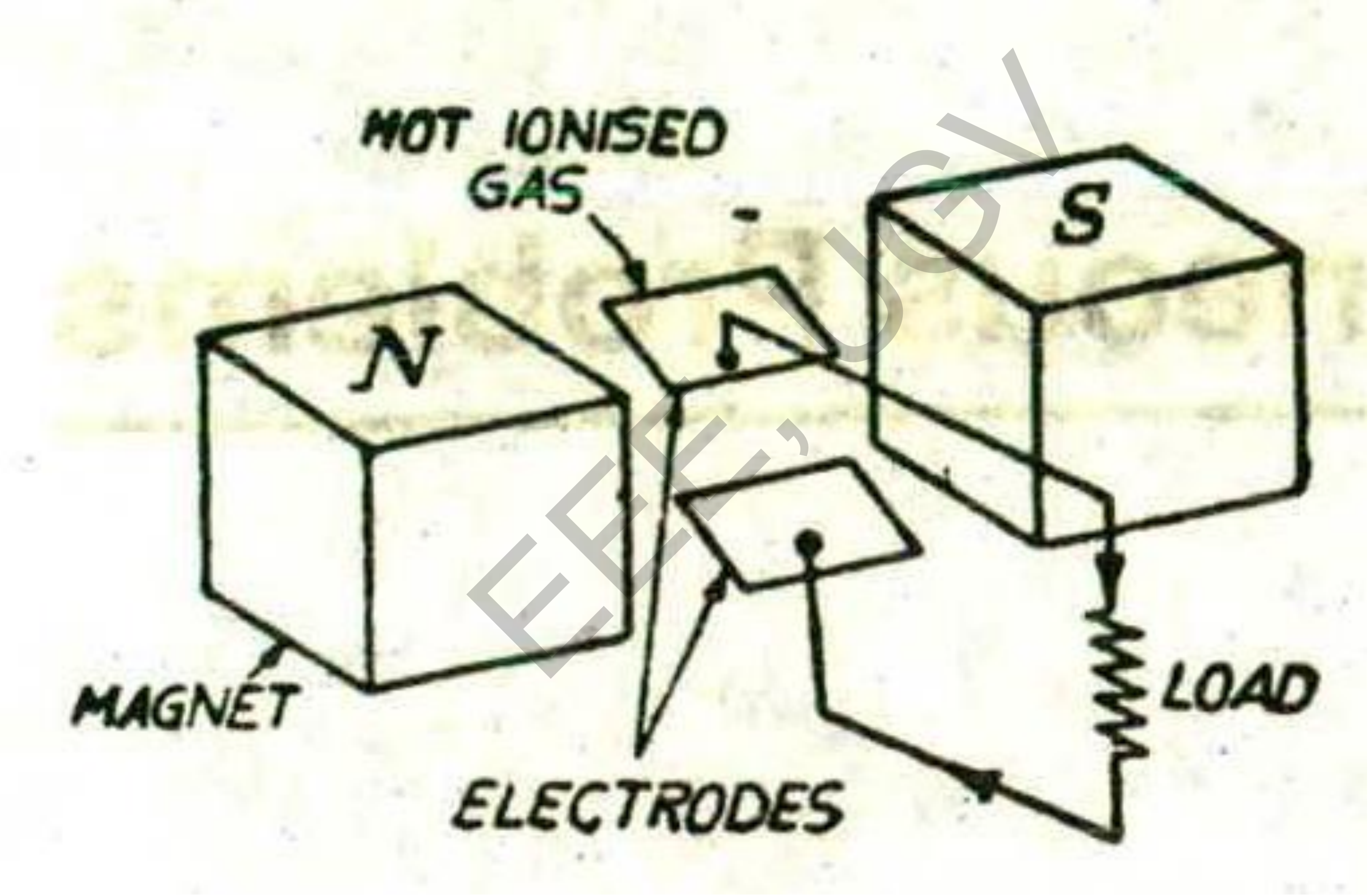
- **An MHD generator is a device for converting heat energy directly into electrical energy without a conventional electric generator.**

Thermal energy → **Electrical energy**

MHD Generator…

- **The principal of MHD power generation is very simple and is based on Faraday's law of electromagnetic induction, which states that when a conductor and a magnetic field moves relative to each other, then voltage is induced in the conductor, which results in flow of current across the terminals.**
- **As in case of conventional electric generator conductor crosses the line of the magnetic field and a voltage is induced. Similarly, in a magneto hydrodynamic generator when an ionized gas flows across the lines of magnetic field a voltage is induced. The ionized gas acts like an electrical conductor.**

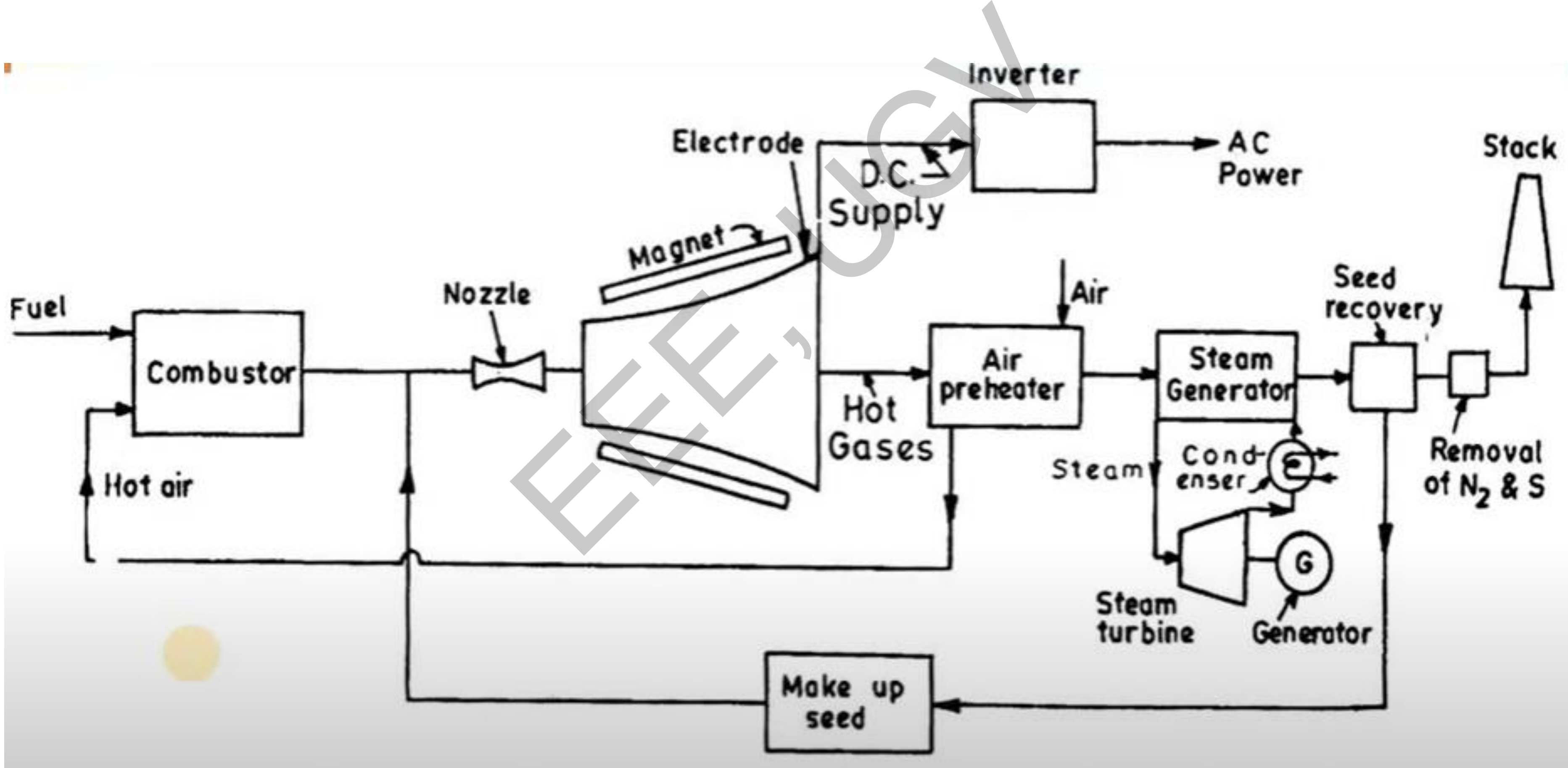
MHD Generator…



Types of MHD Generator

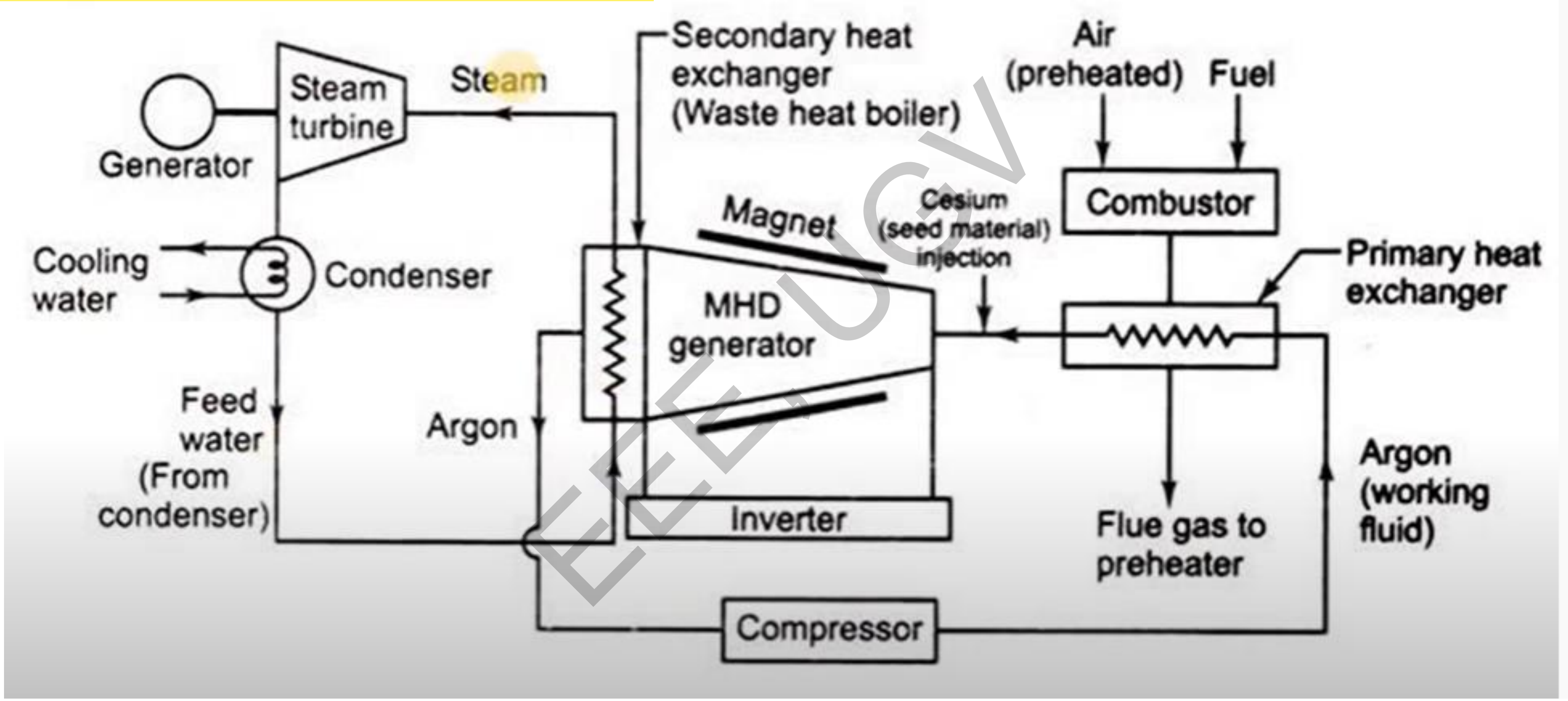
- Two types of MHD Generating systems:
  1) Open cycle ;
     - the working fluid is used on one-through basis and
  2) Closed cycle ;
     - the working fluid is continuously recirculated

Open Cycle MHD Generator



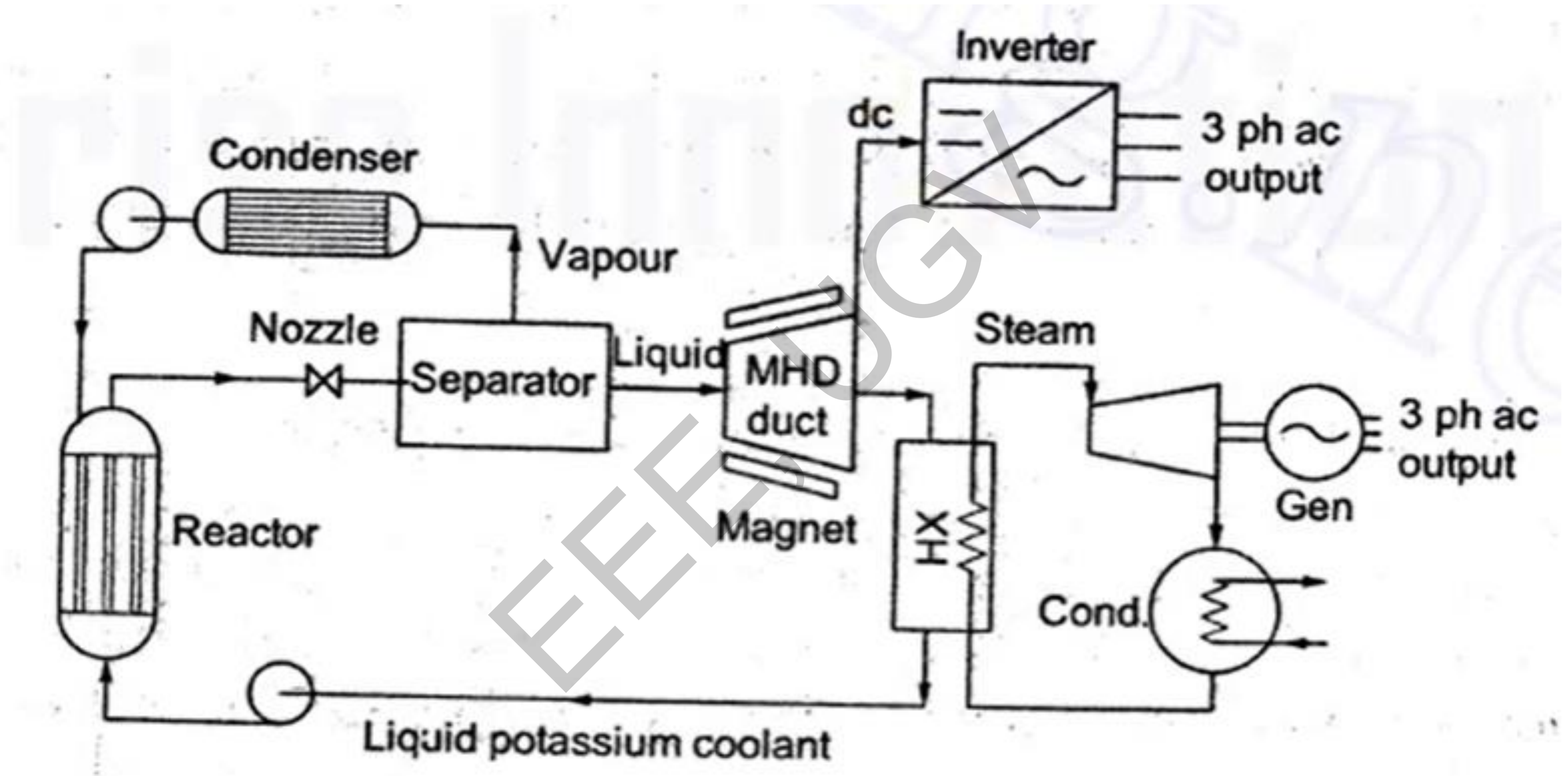
Open cycle MHD generator

Closed Cycle MHD



Temperature requirement is less compared to open cycle (1400 deg C)

Closed cycle MHD Generator



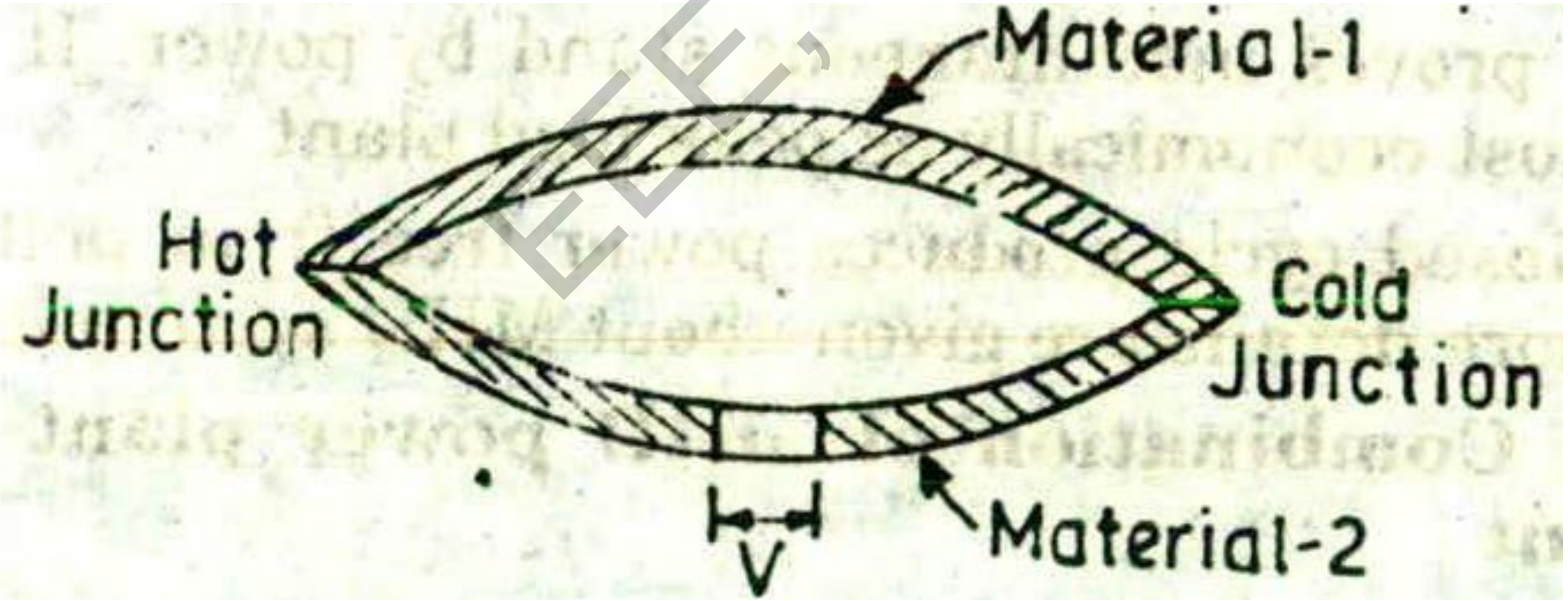
Fast breeder reactor coupled MHD system, with liquid metal as working fluid

MHD Generator…

- **Having no moving parts it has high-reliability, MHD power plants can operate as base load, peaking or semi peaking units and along with a large load variations without significant loss in efficiency.**

Thermo-electric Conversion System

- **The direct conversion of heat energy into electric energy (i.e. without a conventional electric generator) is based on Seebeck effect.**
- **According to Seebeck effect, an emf is produced when in a loop of two dissimilar metals the junctions are kept at different temperatures.**
- **The efficiency of thermo-electric generator depends upon the temperatures of hot and cold junctions.**



Thermo-electric Conversion System

The e.m.f (V) produced is given by

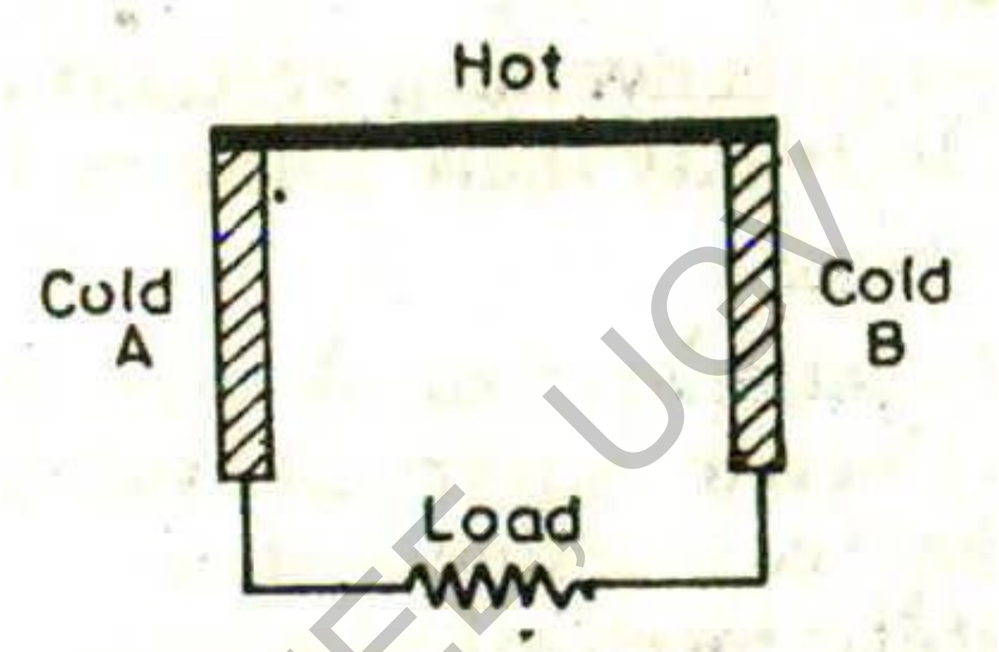
$$V = \alpha_s \times \Delta T$$

where α_s = Seebeck coefficient

ΔT = Temperature difference

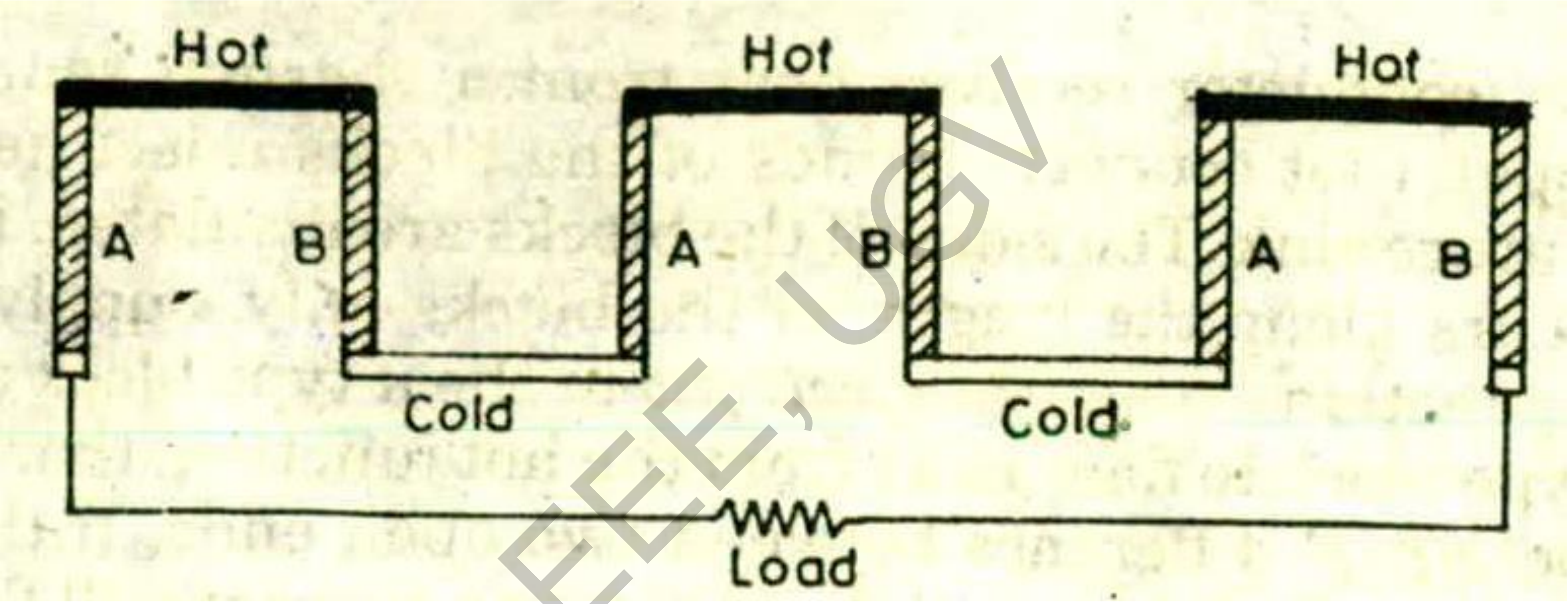
$= T_2 - T_1$

Thermo-electric Power Generator



The materials A and B are joined at the hot end. An electric voltage (or electromotive force) is then generated between the cold ends. A direct current will flow in a circuit or load connected between the ends. For a given thermocouple the voltage and electric power output are increased by increasing the temperature difference between the hot and cold ends.

Thermo-electric Power Generator



- **To increase voltage and power several thermo-couples are connected in series in a thermoelectric power generator.**

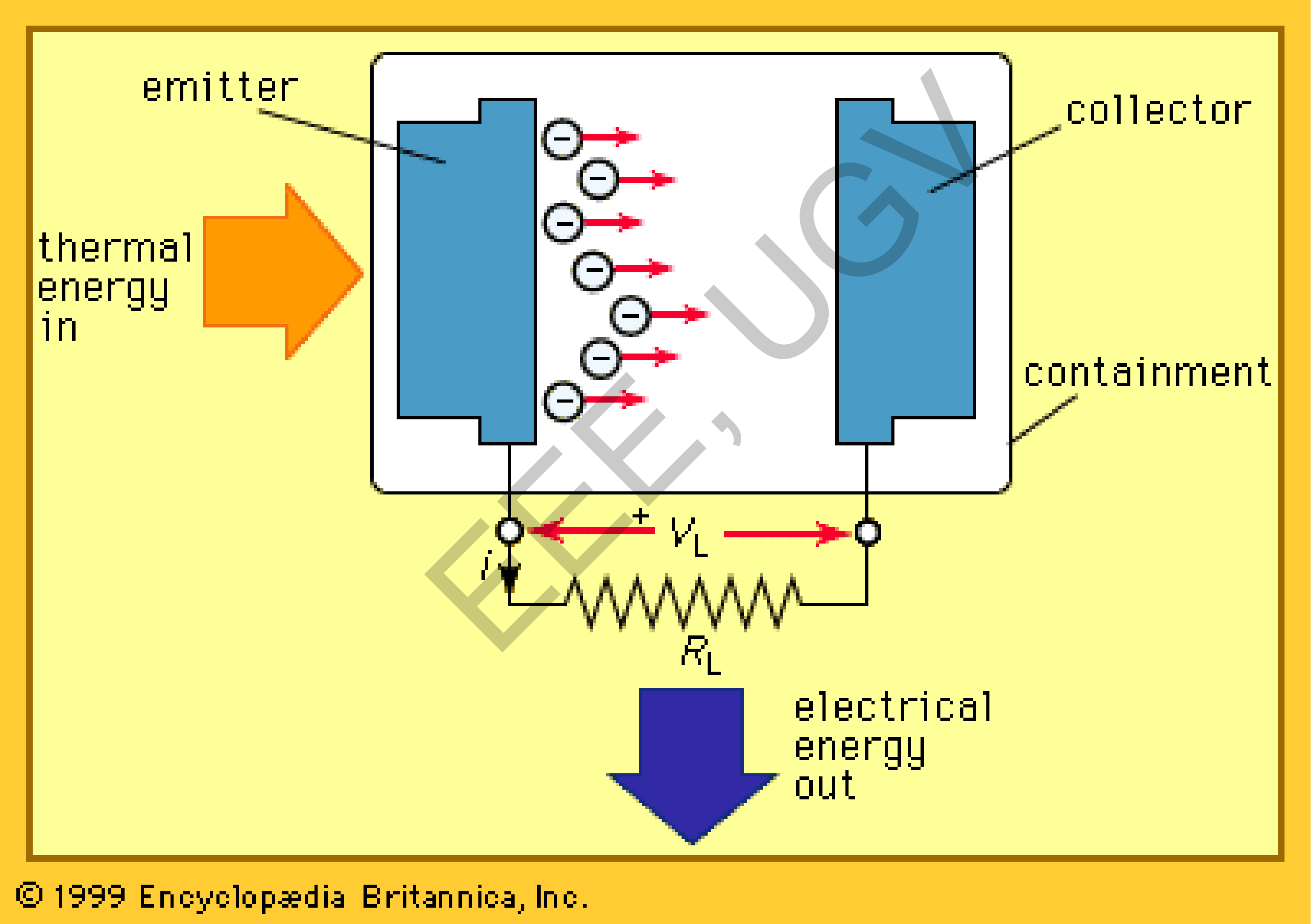
- **The direct current generated can be converted into alternating current by an inverter.**

Thermionic Generation

- **This method of power generation utilizes the thermionic emission effect which means emission of electrons from heated metal surface.**

- **The energy required to extract an electron from the metal is called work function of the metal and depends on the nature of metal and its surface condition.**

Thermionic Converter



Thermionic Converter…

- **The thermionic converter utilizes thermionic emission effect. It consists of two metal (or electrodes) with different work functions sealed into an evacuated vessel on heating one electrode, the electrons are emitted which travel to opposite colder electrode called collector or anode.**
- **The hot electrode (emitter) emits electrons and acquires a positive charge whereas colder electrode collects electrons and becomes negatively changed. A voltage (or electromotive force) thus develops between the electrodes and a direct current starts flowing in the connected load.**

Thermionic Converter…

- **The thermionic converter will continue to generate electric power as long as heat is supplied to the emitter and a temperature difference is maintained between it and the collector.**
- **By thermionic converter, the currents that can be produced are extremely small except in special case of metals at high temperatures.**
- **To achieve a substantial electron emission rate and hence a significant current output as well as a high efficiency the emitter temperature in a thermionic converter containing cesium should be at least 1000 deg C. The efficiency is then about 10 percent. Higher efficiency can be obtained by operating at still higher temperatures.**

- **How a battery works?**

Biomass

Introduction

- **As a result of energy shortages in the years to come, interest in the alternative fuel sources has increased considerably. Biomass is one of the such sources being considered.**

Solar energy → Photosynthesis → Biomass → Energy generation.

Plants, crops, animal dung, etc. can be considered as biomass

Advantages

(i) It is renewable.

(ii) It is environmentally clean.

(iii) It is easily adaptable.

Energy from Biomass

Energy from Biomass is obtained in following three ways:

(i) Biomass in its traditional solid mass (wood and agricultural residue).

The biomass is burnt-directly to obtain the energy.

(ii) Biomass in non-tradition form (converted into liquid fuel).

In this case the biomass is converted into ethanol and methanol to be used as liquid fuels.

(iii) To ferment the biomass anaerobically to obtain a gaseous fuel called bio-gas.

Biomass resources

- **Biomass resources are as follows**

(i) Concentrated wastes like

(a) industrial wastes

(b) municipal solid

(c) manure at large lots.

(ii) Dispersed waste residue like crops residue, disposed manure.

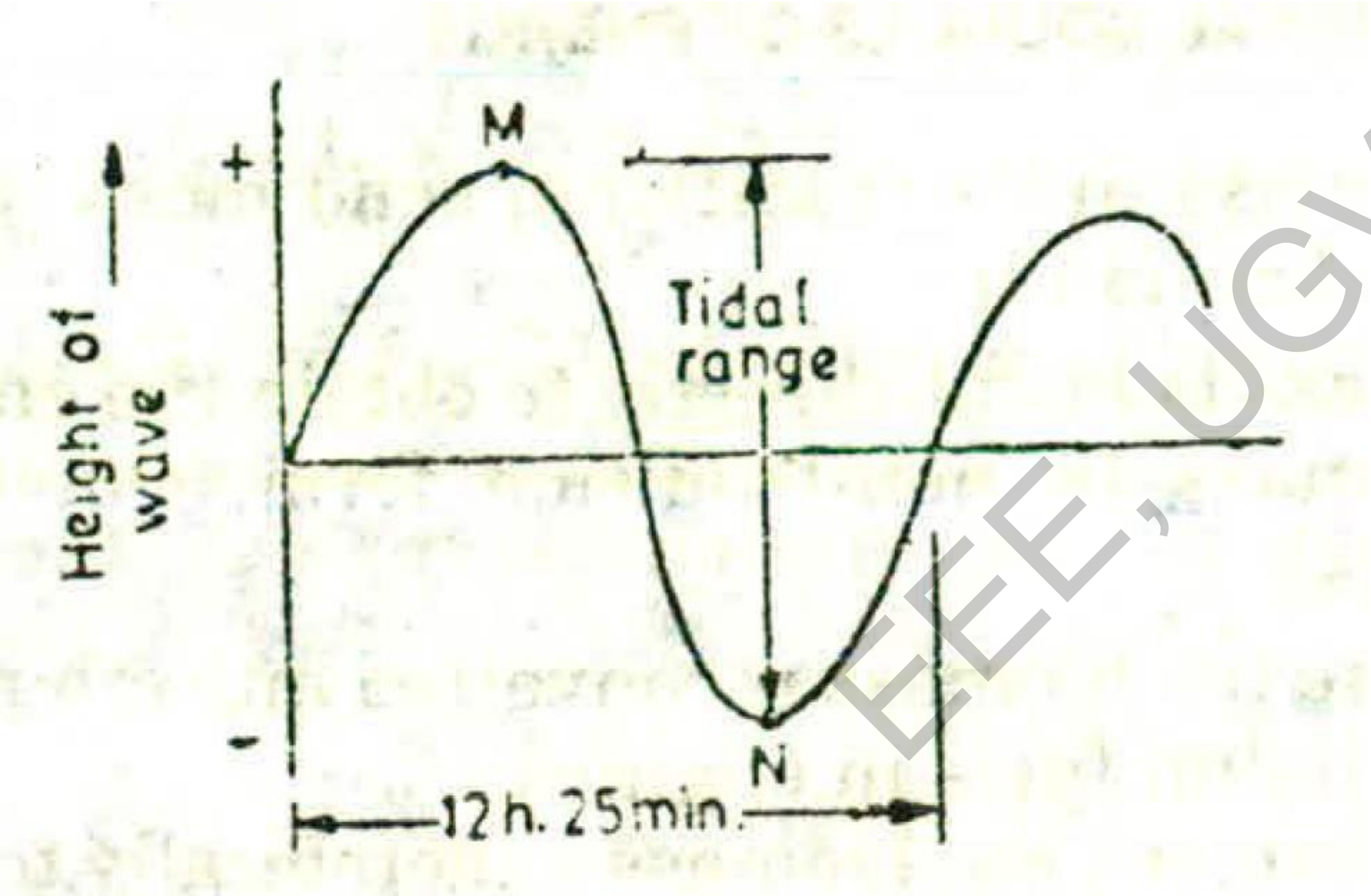
(iii) Harvested biomass, standing biomass.

Tidal Power

Tidal Energy

- **Due to universal gravitational effects of sun and moon on the earth tides in the sea are generated.**
- **Tide is periodic rise and fall of water level of the sea.**
- **When the water is above the mean sea level, it is called flood tide (high tide); and when the water is below the mean sea level, it is known as ebb tide (low tide).**

Tidal energy



The rise and fall of water level follows a sinusoidal curve as shown in Figure with point *M* indicating the high tide point and point *N* indicating the low tide point. The difference between high and low water levels is called the range of the tide.

Site Selection

- **The tidal range at the desired location should be adequate throughout the year.**
- **The site selected for tidal power plant should be free from the wave attack of sea.**
- **There should be no appreciable change in tidal pattern at the proposed site.**
- **The site at which tidal power plant is to be located should not have excessive sediment load.**

Components

The three main components of a tidal power plant are as follows.

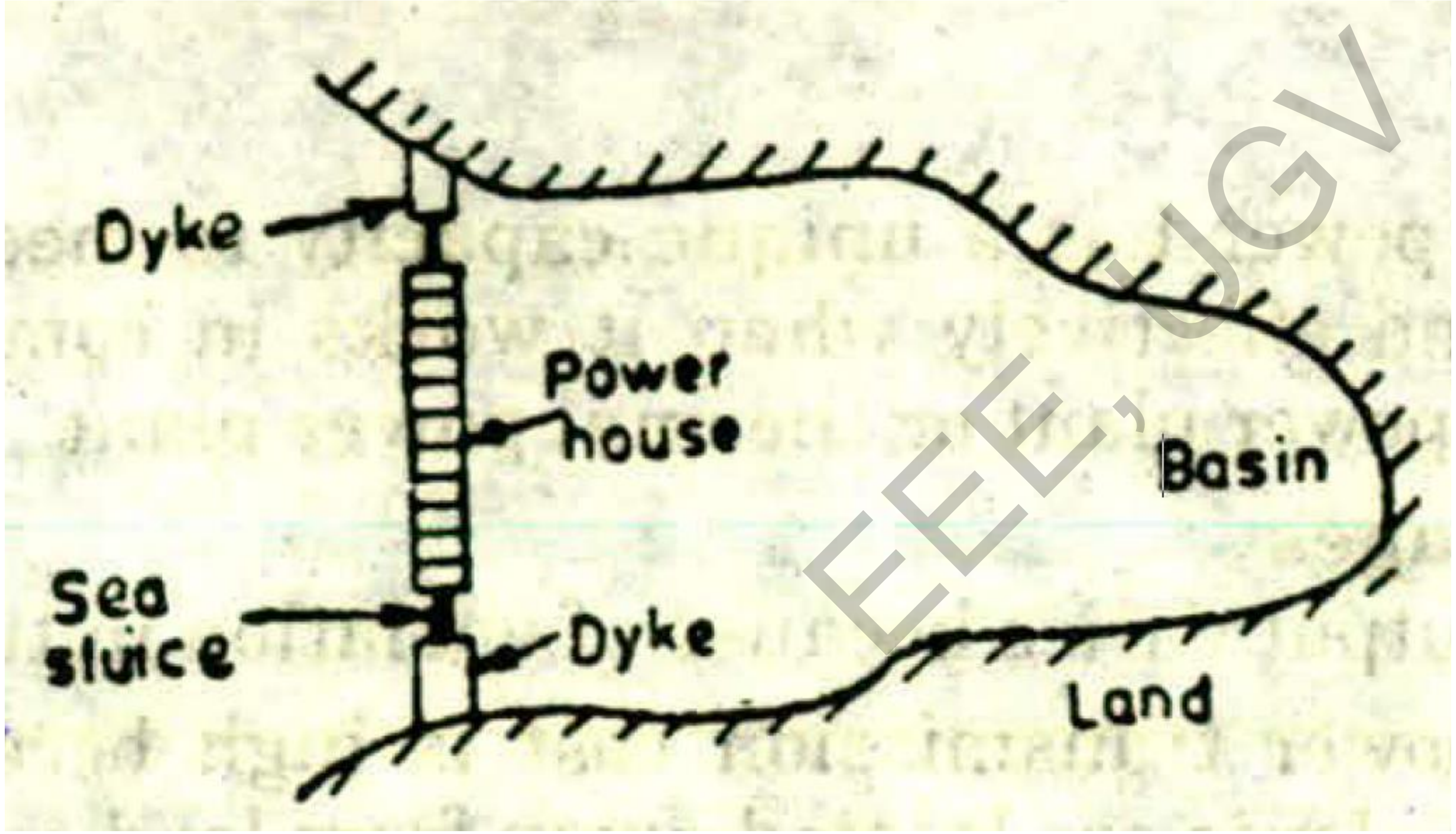
(i) The dyke to form basin

(ii) Sluice ways from the basin to the sea and vice versa

(iii) The power house.

The turbine, electric generators and other auxiliary equipment are the main equipment of power house.

Single basin tidal power plant



In a single basin one way tidal power plant, a basin is allowed to get filled during the flood tide and during the ebb tide, the water flowing from the basin to the sea through the turbine and generates power. The power is available for a short duration during ebb tide.

In single basin two way tidal power plant, the power is generated both during flood tide as well as ebb tide. The direction of flow through the turbines during the ebb and flood tides alternates but machine acts as a turbine for either direction of flow.

- **Double basin tidal power plant**

Advantages

- **It is free from pollution.**
- **It is inexhaustible and does not depend on rain.**
- **Tidal power plants do not require large area of valuable land because they are located on sea shore.**
- **Tidal power has a unique capacity to meet peak power demand effectively when it works in combination with hydropower plant or thermal power plant.**

Disadvantages

- **The output varies because of variation in tidal range.**
- **The power transmission cost is high because the tidal power plants are located away from load centres.**
- **Sedimentation and siltation of basins are the problems associated with tidal power plants.**
- **Because of variable tidal range the turbines have to work on a wide range of variable head.**
- **Capital cost of the plant is high.**

Geothermal Energy

Introduction

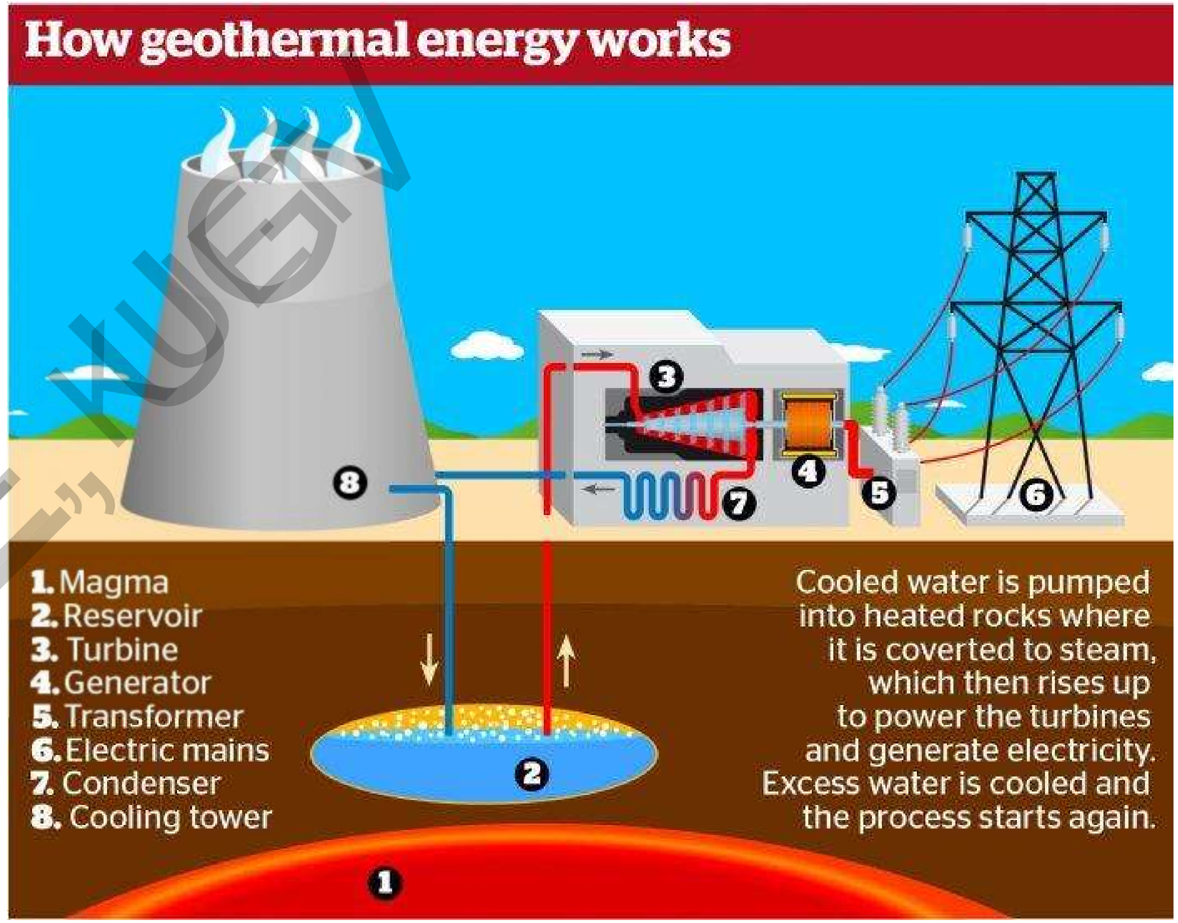
Geothermal comes from the Greek words geo, meaning earth, and thermo, meaning heat.

- **Geothermal energy is the heat from the earth. It's clean and sustainable.**
- **Geothermal power plants use superheated fluids from the earth's geothermal resources to generate electricity.**

Source: http://www.renewableenergyworld.com/geothermal-energy/tech.html

How a Geothermal Plant Works

- The **natural heat of the earth** creates geothermal resources.
- This heat comes from molten rock, **called magma**, located at the earth's core deep below the geothermal resource.
- Over thousands of years, **rainwater seeps through cracks in the earth's surface** and collects in underground reservoirs.
- The magma heats the water until it becomes a **superheated fluid.**



https://grendz.com/pin/6959/

How a Geothermal Plant Works…

- To reach the superheated fluids **wells are drilled 5,000 to 10,000 feet** below the surface of the earth.
- These wells, called production wells, bring the **superheated fluids to the earth's surface** where it can be used to generate electricity for homes and business.

Source: https://www.youtube.com/watch?v=kjpp2MQffnw

Advantages

- Clean fuel source
- No health hazards like thermal (coal) power
- No fuel costs
- Provides predictable, constant power (not intermittent like wind or solar)
- High load factor like thermal and nuclear power

Source: A Smart Energy Future 20 Unit 1: Benefits of a Smart Grid © Education Development Center, 2015, 3rd Edition

Disadvantages

1. **Not Widespread Source of Energy**: Since this type of energy is not widely used therefore the unavailability of **equipment, staff, infrastructure, training** pose hindrance to the installation of geothermal plants across the globe. **Not enough skilled manpower and availability of suitable build** location pose serious problem in adopting geothermal energy globally.

2. **High Installation Costs**: To get geothermal energy, requires installation of power plants, **to get steam from deep within the earth** and this require huge one time investment and require to hire a certified installer and skilled staff needs to be recruited and relocated to plant location. Moreover, electricity towers, stations need to set up to move the power from geothermal plant to consumer.

3. **Can Run Out of Steam** : Geothermal sites can run out of steam over a period of time **due to drop in temperature or if too much water is injected to cool the rocks** and this may result huge loss for the companies which have invested heavily in these plants. Due to this factor, companies have to do extensive initial research before setting up the plant.

Source: http://www.conserve-energy-future.com/disadvantages_geothermalenergy.php

Disadvantages…

4. **Suited to Particular Region : It is only suitable for regions which have hot rocks below the earth and can produce steam over a long period of time. For this great research is required which is done by the companies before setting up the plant and this initial cost runs up the bill in setting up the geothermal power plant. Some of these regions are near hilly areas or high up in mountains.**

5. **May Release Harmful Gases : Geothermal sites may contain some poisonous gases and they can escape deep within the earth, through the holes drilled by the constructors. The geothermal plant must therefore be capable enough to contain these harmful and toxic gases.**

6. **Transportation : Geothermal Energy can not be easily transported. Once the tapped energy is extracted, it can be only used in the surrounding areas. Other sources of energy like wood, coal or oil can be transported to residential areas but this is not a case with geothermal energy. Also, there is a fear of toxic substances getting released into the atmosphere.**

Source: http://www.conserve-energy-future.com/disadvantages_geothermalenergy.php

Fuel Cell

Advantages & Disadvantages

- It is an electro-chemical device which converts chemical energy directly into electrical energy.

Advantages:

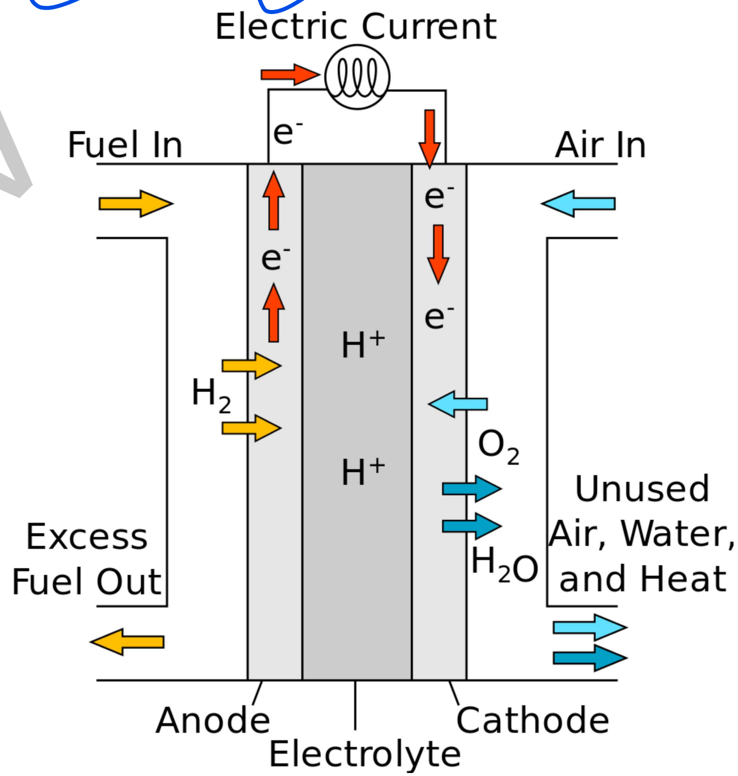
- It is simple.
- It has high power to weight ratio.
- High efficiency

Disadvantages:

- Its cost is high.
- It has relatively short life particularly at high temperatures.
- It is very essential to select proper materials for components so that the reaction cannot attack them.

Principle of Operation

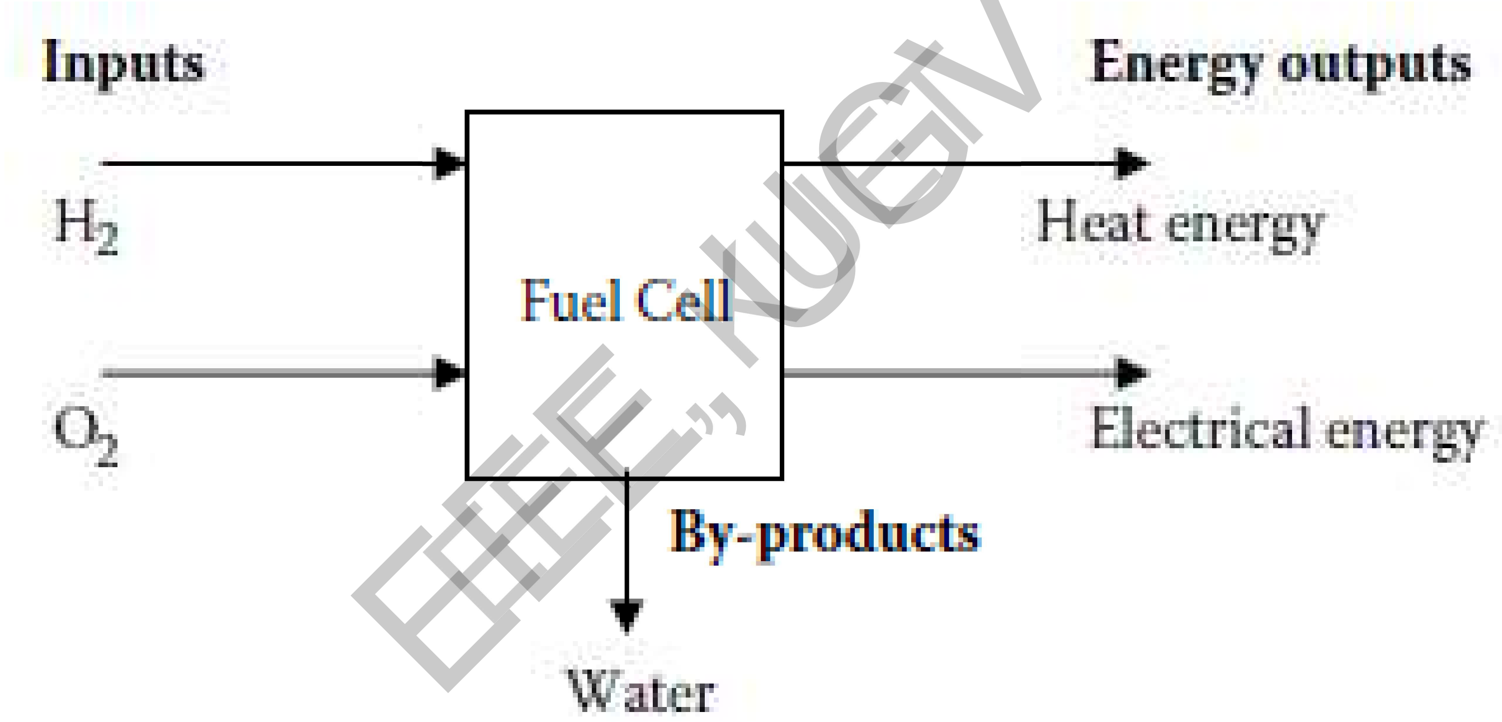
- **There are two chambers. In one chamber, hydrogen is introduced and in other chamber, oxygen is introduced.**
- **The two chambers are separated by an electrolyte, which may be solid or liquid. The various electrolytes used are Potassium hydroxide, Zirconia oxide porous ceramic and solid polymers.**



Polymer electrolyte membrane ---Proton exchange membrane (PEM) fuel cell

https://en.wikipedia.org/wiki/Proton_exchange_membrane_fuel_cell#/media/File:Proton_Exchange_Fuel_Cell_Diagram.svg
G. R. Nagpal, Power plant engineering, 15th edition.

Principle of Operation…



Source: James A. Momoh, Electric Power Distribution, Automation, Protection, and Control, CRC Press, 2007.

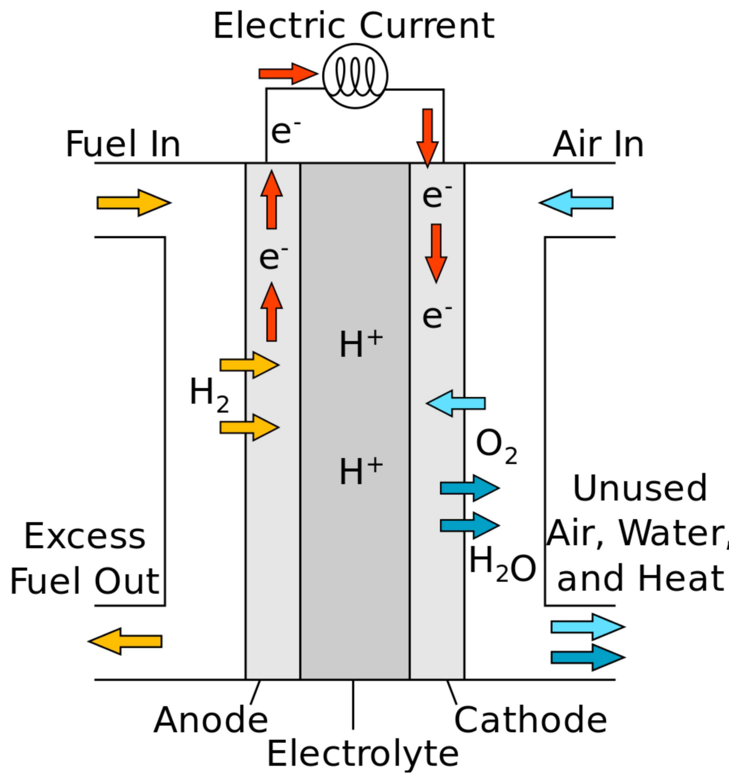
Principle of Operation…

- **Hydrogen ions are produced by the dissociation of hydrogen molecules at the anode electrolyte interface.**

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

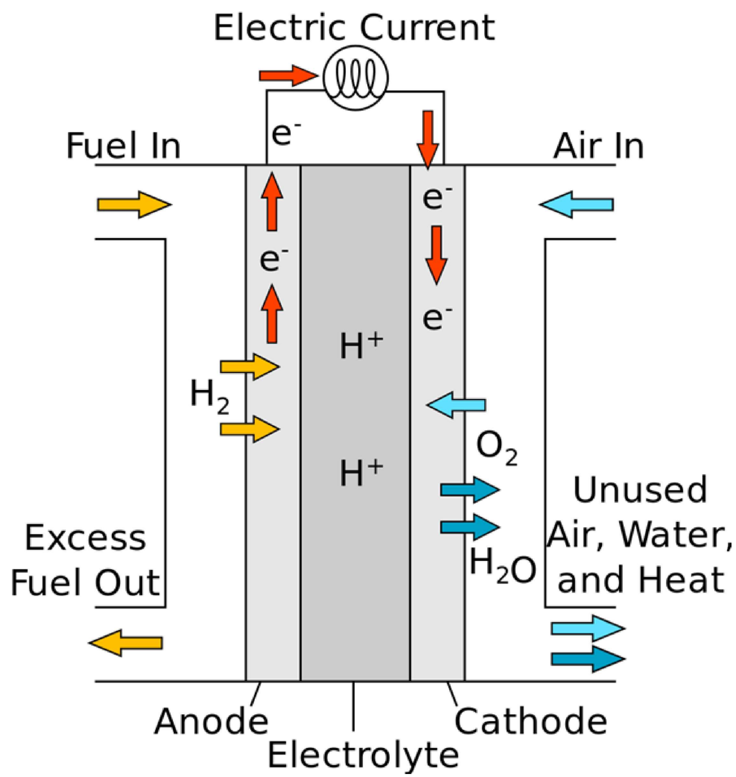
- **The electrolyte material acts as a sieve and the hydrogen ions can migrate through the material.**

- **The electrical load is connected between anode and cathode.**



Principle of Operation…

- **The electrons so formed return to the fuel cell at cathode leaving a positive charge at anode. The hydrogen ions diffuse through electrolyte and when they reach cathode they combine with electrons and oxygen molecules and form water.**



$$4H^{+} + 4e^{-} + O_2 \rightarrow 2H_2O$$

Hybrid Power Systems

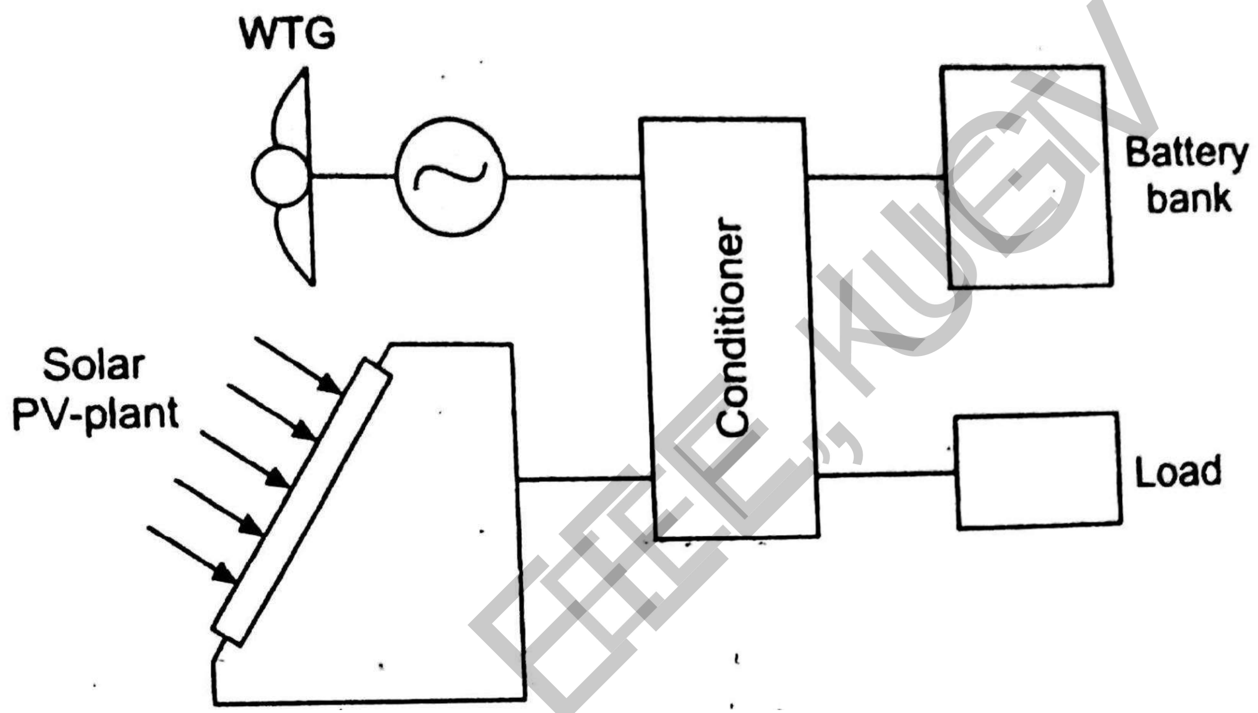
Introduction

Hybrid power are combinations between different technologies to produce power.

Hybrid systems, as the name implies, combine two or more modes of electricity generation together, usually using renewable technologies such as solar photovoltaic (PV) and wind turbines. Hybrid systems provide a high level of energy security through the mix of generation methods, and often will incorporate a storage system (battery) or small fossil fueled generator to ensure maximum supply reliability and security.

Source: https://en.wikipedia.org/wiki/Hybrid_power

Wind-PV Hybrid System



RE sources are variable in nature

Source: D. P. Kothari and others, Renewable energy sources and emerging technologies, 2nd edition, PHI Learning Private Ltd., 2013

Wind-PV Hybrid System…

- **During the day when the sun shines, the solar PV plant generates dc electric energy.**
- **The power conditioner converts dc to ac and supplies power to the load.**
- **During favorable wind speed, the wind turbine generator produces ac electrical power. It supplies power to the load and excess energy after conversion to dc is stored by the battery bank.**
- **The plant may operate as stand-alone or may be connected to the grid.**

Source: D. P. Kothari and others, Renewable energy sources and emerging technologies, 2nd edition, PHI Learning Private Ltd., 2013

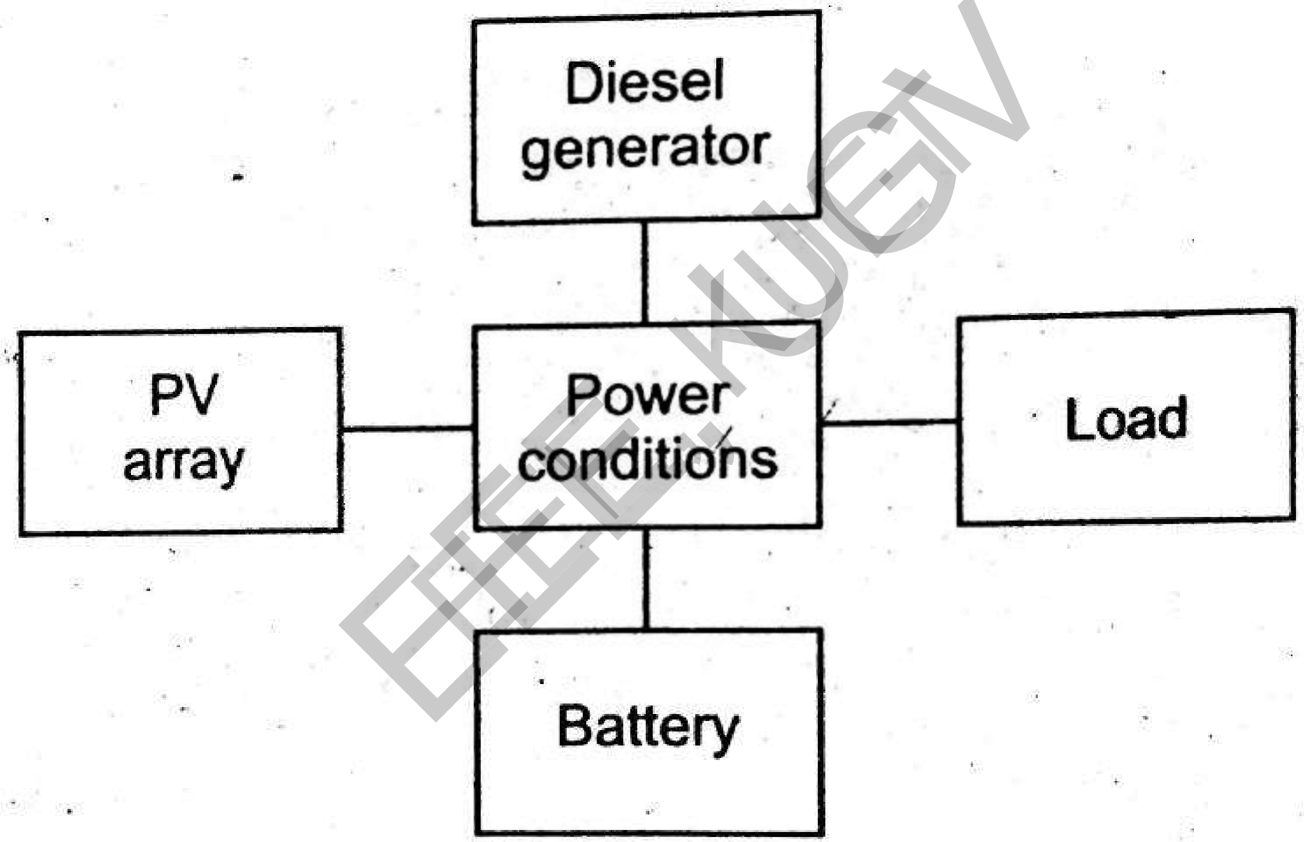
Wind-PV Hybrid System

- **Wind and solar hybrid energy systems are located in open terrains away from multi-storey buildings and forests.**

- **Locations are selected in those areas where the sunshine and wind are favorable for more than 8 months during a year.**

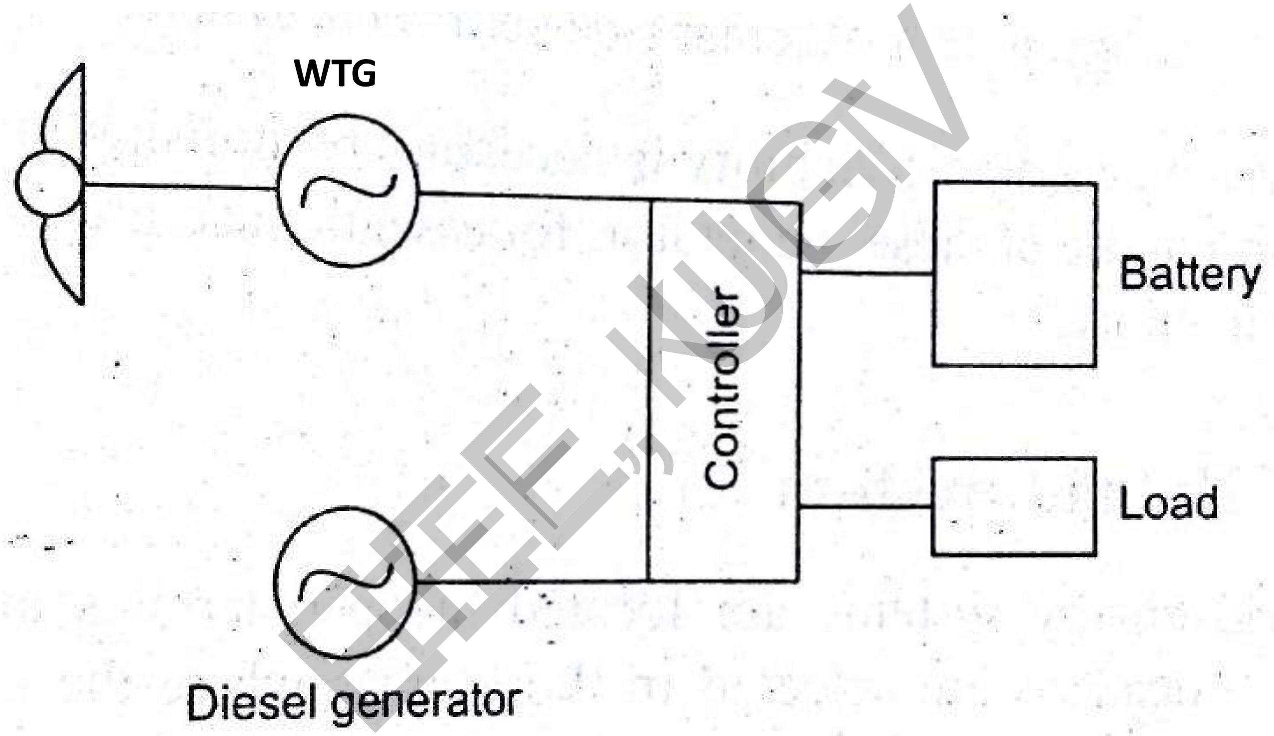
Source: D. P. Kothari and others, Renewable energy sources and emerging technologies, 2nd edition, PHI Learning Private Ltd., 2013

PV-Diesel Hybrid System



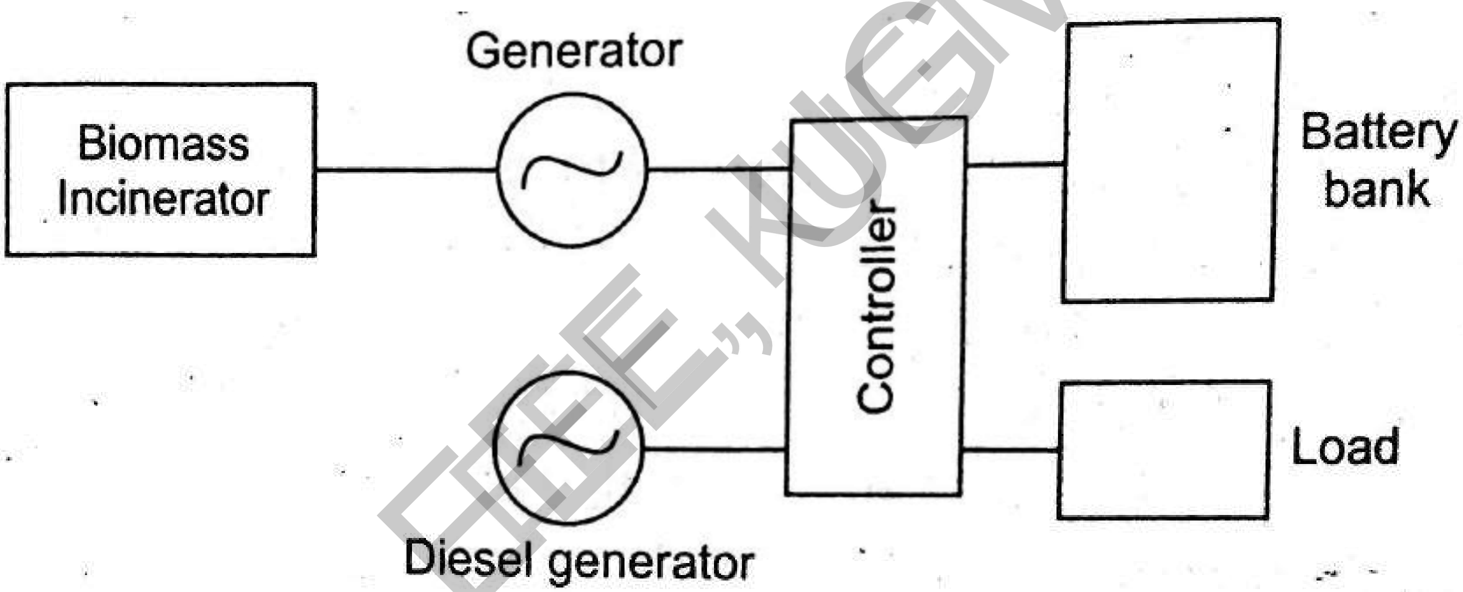
Source: D. P. Kothari and others, Renewable energy sources and emerging technologies, 2nd edition, PHI Learning Private Ltd., 2013

Wind-Diesel Hybrid System



Source: D. P. Kothari and others, Renewable energy sources and emerging technologies, 2nd edition, PHI Learning Private Ltd., 2013

Biomass-Diesel Hybrid System



Source: D. P. Kothari and others, Renewable energy sources and emerging technologies, 2nd edition, PHI Learning Private Ltd., 2013

Thank You

Reference: G.R Nagpal book for MHD generator (Chapter 9), page 539 to 541. Chapter 11, page 621-624.

9.1 Magneto-hydro Dynamic (MHD) Generator

Principle. The principle of a magneto hydro dynamic (MHD) generator is based on Faraday's law of electromagnetic induction which states that a changing magnetic field induced an electric field in any conductor located in it. This electric field while acting on the free charges in the conductor causes a current to flow. As in case of conventional electric generator conductor crosses the line of the magnetic field and a voltage is induced. Similarly in a magneto hydrodynamic generator when an ionised gas flows across the lines of magnetic field a voltage is induced. The ionised gas acts like an electrical conductor. The gas used may have a temperature between 2000°–3000°K.

M.H.D. generator is a highly efficient heat engine which directly converts thermal energy into electricity. It is the latest technique of advanced method of power generation where efficiency as high as 60% can be achieved as compared to about 35% efficiency of conventional thermal power stations. A M.H.D. generator requires a suitable working fluid which is electrical conducting. The working fluid is a partially ionised gas. The concepts of M.H.D. generation depends much more on the conductivity of the gas. The conductivity of the gas is a function of temperature. Gases become conducting when their atoms of molecules are stripped of one or more electrons thermally, electrically or by using radiations. However to achieve thermal ionization of the products of combustion of fossil fuel or inert gases extremely high temperatures are necessary. Reasonable ionisation and hence reasonable value of electrical conductivity is obtained at temperature around 2000 to 3000°K when the gases are seeded with additives of easily ionising materials (alkali metals). This method of power generation will reduce environmental pollution considerably.

The initial cost of setting up of an M.H.D. power plant is anticipated to be slightly higher than that of conventional thermal

Mathematical Problem

A certain radioactive substance has a disintegration constant $\lambda = 1.44 \times 10^{-3}$ per hour. In what time will 75% of the initial number of atoms disintegrate?

Solution:

$$Here,\ \lambda = 1.44 \times 10^{-3} \text{ per hour}$$

$$N = N_0 - \frac{3}{4} N_0 = \frac{N_0}{4}$$

t=?

$$N = N_0 e^{-\lambda t}$$

$$\Rightarrow \frac{1}{4} = e^{-\lambda t}$$

$$\Rightarrow t = \frac{\log_e 4}{\lambda}$$

$$= 962.9\ hours$$

Problem

- A newly born neutron of 4.8 MeV is to be slowed to 0.025 eV in a graphite moderator. Assuming all collisions to be elastic, calculate the logarithmic energy decrement representing the neutron energy loss per elastic collision and the number of collisions necessary.

$$\xi = 1 - \left[\frac{(A-1)^2}{2A} ln \frac{A+1}{A-1}\right]$$

$$n = \frac{ln \frac{E_{n,i}}{E_{n,f}}}{\xi}$$

$$E_{n,i} = 4.8 \text{ MeV}$$

$$E_{n,f} = 0.025 \text{ eV}$$

led chain reaction takes place so that the heat energy released can be controlled.

Let V = Volume of energy

N = Fuel atoms/m^3

n = Average neutron density, *i.e.* number per m^3

a = Fission cross section

ϕ = Neutron flux

v = Average speed of neutrons m/sec.

F ission cross-section represents the probability of fission per incident neutron. For example if y is the number of incident neutron then those causing fission $= a \times y$. Neutron flux is the number of neutrons crossing a plane of area one metre square held at right angle to velocity v.

$$\phi = n \times v$$

S = total fuel atoms in reactor $= N.V.$

h = number of incident neutrons per second on fuel atoms

$$= S \times \phi = n.v.\ N.V.$$

x = Number of neutrons causing fission per second

$$= h \times a = n.v.\ N.V.a.$$

Now 3.1×10^{10} fission per second produce a power of one watt (See example 5.3)

P = Power of nuclear reactor

$$= \frac{x}{3.1 \times 10^{10}} = \frac{n.v.N.V.a.}{3.1 \times 10^{10}} \text{ watts}$$

Let the fuel used in the reaction be U^{235}

Mass per atom of U^{235}

$$= \frac{\text{At. weight of } U^{235}}{\text{Avogadro Number}} = \frac{235}{6.02 \times 10^{26}} \text{ kg.}$$

Mass of NV atoms $= N.V. \times$ Mass per atom

$$= NV \times \frac{235}{6.02 \times 10^{26}} = M \text{ kg (say)}$$

$$\therefore \quad NV = \frac{6.02 \times 10^{26} \times m}{235}$$

Now $$P = \frac{n.v.N.V.a.}{3.1 \times 10^{10}} \text{ watts}$$

$$= \frac{\phi \times 6.02 \times 10^{26} M \times 582 \times 10^{-28}}{3.1 \times 10^{10} \times 235}$$

$$= 4.8 \times 10^{-12} M\phi \text{ watts.}$$

5.33 Reactor Power Control

The power released in a nuclear reactor is proportional to the number of mole fissioned per unit time this number being in turn proportional to density of the neutron flux in the reactor. The power of a nuclear reactor can be controlled by shifting control rods which may be either actuated manually or automatically.

Power control of a nuclear reactor is simpler than that of conventional thermal power plant because power of a nuclear reactor is a function of only one variable whereas power of a thermal power plant depends on number of factors such as amount of fuel, its moisture content, air supply etc. This shows that power control of thermal plant requires measuring and regulating several quantities which is of course considerably more complicated.

5.34 Nuclear Power Plant Economics

Major factors governing the role of nuclear power are its economic development and availability of sufficient amount of nuclear fuel.

It is important to extract as much energy from a given amount of fuel as possible. The electrical energy extracted per unit of amount of fuel or expensive moderator might be called the "material efficiency". In a chain reactor the high material efficiency as well as high thermal efficiency leads to low over all energy cost.

Since the most attractive aspect of nuclear energy is the possibility of achieving fuel costs considerably below that for coal, all nuclear power system being considered for large scale power production involve breeding or regenerative systems. This program includes the development of the technology of low neutron absorbing structural materials such as zirconium, the use of special moderating materials such a D_2O and the consideration of special problems associated with fast reactors. In so far as economic factors are concerned it is necessary to consider neutron economy in a general way such as that measured by the conversion ratio of the system. The conversion ratio is defined as the atoms of new fuel produced in fertile material per atom of fuel burnt. The conversion ratio varies regulating and protection, steam turbine and generator. To meet the performance criteria including safe radiation levels in the plant area and radioactive effluents during operation the stage-wise clearance from Atomic Energy Regulatory Board (AERB) is mandatory before filling heavy water, loading fuel making the reactor critical, raising steam, synchronising and reaching levels of 25%, 50%, 75% and 100% of full power. The commissioning period lasts for about two years.

Example 5.1. *Calculate the number of fission in uranium per second required to produce 2 kW of power if energy released per fission is 200 meV.*

Solution. P = Power = 2 kW

E = Energy released per fission = 200 MeV

$= 200 \times 10^6 \text{ eV} = 200 \times 10^6 \times 1.6 \times 10^{-19} \text{j}$

$= 3.2 \times 10^{-11} \text{j}$

P = 2 kW = 2000 Watts = 2000 joules/sec.

N = Number of fissions per sec.

$$= \frac{P}{E} = \frac{2000}{3.2 \times 10^{-11}} = 6.25 \times 10^{13}. \textbf{ Ans.}$$

Example 5.2. *A nuclear reactor uses U^{235} as fuel. If the mass of fuel is 1.2 kg and neutron flux is 10^{16} per sec. Calculate the power of reactor.*

Solution. M = Mass of fuel = 1.2 kg

ϕ = Neutron flux = 10^{16}/sec

P = Power of reactor

$= 4.8 \times 10^{-12} \, m \, \phi$ watts

$= 4.8 \times 10^{-12} \times 1.2 \times 10^{16}$

$= 57.6 \times 10^3$ watts = 57.6 kW.

Example 5.3. *Calculate the fission rate of U^{235} for producing power of one watt if 200 MeV if energy is released per fission of U^{235}.*

Solution. P = Power = 1 watt

E = Energy released per fission of U^{235} nucleus

$$= 200 \text{ MeV} = 200 \times 1.6 \times 10^{-13} \text{ J}$$

$$= 3.2 \times 10^{-11} \text{ watt sec.}$$

as $1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J}$

Fission rate of producing one watt of power

$$= \frac{P}{E} = \frac{1}{3.2 \times 10^{-11}} = 3.1 \times 10^{10} \text{ fissions/sec.}$$

Example 5.4. *A railway engine is driven by atomic power at an efficiency of 40% and develops an average power of 1600 kW during 8 hour run from one station to another. Determine how much U^{235} would be consumed on the run if each atom on fission releases 20 0 MeV.*

Solution. Output = 1600 kW

Efficiency = 0.4

$$0.4 = \frac{\text{Output}}{\text{Input}}$$

$$\text{Input} = \frac{1600}{0.4} = 4000 \text{ kW} = 4 \times 10^6 \text{ watts.}$$

$$E = \text{Energy released per fission} = 200 \text{ MeV}$$

$$= 200 \times 1.6 \times 10^{-12} \text{ J} = 3.2 \times 10^{-11} \text{ J}$$

$$t = \text{Time} = 8 \text{ hours} = 8 \times 3600 \text{ seconds.}$$

Input nuclear energy required = Input × t

$$= 4 \times 10^6 \times 8 \times 3600 \text{ J} = 115.2 \times 10^9 \text{ J}$$

Number of U^{235} atoms required for 8 hour run

$$= \frac{115.2 \times 10^9}{E} = \frac{115.2 \times 10^9}{3.2 \times 10^{-11}} = 36 \times 10^{20}$$

We know that 235 gm of U^{235} contains 6.02×10^{23} atoms (Avogadro's hypothesis).

Mass of U^{235} consumed

$$= \frac{36 \times 10^{20} \times 235}{6.02 \times 10^{28}} = 1.4 \text{ gm.}$$

Example 5.5. *Determine the energy released by the fission of 1.5 gm of U^{235} in kWh assuming that energy released per fission is 200 MeV.*

Avogadro number = 6.025 × 10^{23}

Mass of Uranium = 235 a.m.u.

Solution. n = Number of atoms in 1.5 gm of U^{235}

$$= \frac{1.5 \times 6.025 \times 10^{23}}{235}$$

E_1 = Energy released per fission = 200 MeV

$$= 200 \times 10^6 \times 1.6 \times 10^{-19} = 3.2 \times 10^{-11} \text{ Joules}$$

E = Energy released by 1.5 gm of U^{235}

$$= n \times E_1 \text{ Joules}$$

$$= \frac{1.5 \times 6.025 \times 10^{23}}{235} \times \frac{3.2 \times 10^{-11}}{60 \times 60 \times 10^3} \text{ kWh}$$

$$= 3.42 \times 10^4 \text{ kWh.}$$ **Ans.**

Example 5.6. *Determine the fission energy released when a U-235 nucleus is fissioned by a thermal neutron and two fission fragments and two neutrons are produced. The average binding energy per nucleon is 8 MeV in the fissioned U-235 nucleus and 8.8 MeV in the fission fragments.*

Solution. E = fission energy released

$$= 234 \times 8.8 - 236 \times 8$$

$$= 158.4 \text{ MeV.}$$

PROBLEMS

5.1. What is a chain reaction ? How it is controlled ?

5.2. What is a nuclear reactor ? Describe the various parts of a nuclear reactor.

5.3. What are different types of reactors commonly used in nuclear power stations ? Describe the fast breeder reactor ? What are its advantages over sodium graphite reactor ?

5.4. How waste is disposed off in a nuclear power station ? What are main difficulties in handling radioactive waste ?

5.5. Discuss the various factors to be considered while selecting the site for nuclear power station. Discuss its advantages and disadvantages.

5.6. Write short notes on the following :
(*a*) Boiling water reactor (B.W.R.)
(*b*) Pressurised water reactor (P.W.R.)
(*c*) Multiplication factor.
(*d*) Fertile and fissionable material.

Example 11.1. *At a tidal site the observed difference between the high and low water tide is 9 m. The basin area is 0.6 sq. km. which can generate power for 3 hours in each cycle. The average available head is 8.5 m. and over all efficiency of generation is 75% calculate the yearly power out put. Specific weight of sea water is 1025 kg/m^3 and there are 705 full tidal cycles in a year.*

Solution.

A = Area of basin

= 0.6 sq. km. = 0.6×10^6 m^2

h = Difference in water tide = 9 m

v = volume = $A \times h$

= $0.6 \times 10^6 \times 9 = 5.4 \times 10^6$ m^3

T = Time = 3 hours

Q = Average discharge

$$Q = \frac{V}{T}$$

$$= \frac{5.4 \times 10^6}{3 \times 3600} = 500 \text{ m}^3\text{/S}$$

ω = specific weight of water = 1025 kg/m^3

$$P = \text{Power} = \frac{\omega Q H}{75} \times \eta$$

where H = Average available head = 8.5 m

η = Efficiency = 0.75

$$P = \frac{1025 \times 500 \times 8.5}{75} \times 0.75$$

$= 4.3 \times 10^4$ H.P.

E = Energy per cycle

$= P \times 0.736 \times T$

$= 4.3 \times 10^4 \times 0.736 \times 3 = 9.3 \times 10^4$ kWh.

N = Number of tidal cycle per year = 705

Total out put per year

$= E \times N = 9.3 \times 10^4 \times 705$

$= 6.4 \times 10^7$ kWh.

Problem

Example 2.6. *A hydro-electric generating station is supplied from a reservoir of capacity 5×10^6 cubic metres at a head of 200 metres. Find the total energy available in kWh if the overall efficiency is 75%.*

Solution.

Electrical Energy available, $E = m \times g \times H \times \eta_{overall}$

$= 5 \times 10^6 \times 1000 \times 9.81 \times 200 \times 0.75$ **Watt-Sec**

Mass of 1 m^3 of water is 1000 kg

$$= \frac{5 \times 10^6 \times 1000 \times 9.81 \times 200 \times 0.75}{3600 \times 1000} \; kWh$$

$= 2.044 \times 10^6 \; kWh$

(i)

Example 2.3. *A steam power station spends Rs. 30 lakhs per annum for coal used in the station. The coal has a calorific value of 5000 kcal/kg and costs Rs. 300 per ton. If the station has thermal efficiency of 33% and electrical efficiency of 90%, find the average load on the station.*

Solution.

$$\text{Overall efficiency, } \eta_{overall} = 0\cdot33 \times 0\cdot9 = 0\cdot297$$

$$\text{Coal used/annum} = 30 \times 10^5/300 = 10^4 \text{ tons} = 10^7 \text{ kg}$$

$$\text{Heat of combustion} = \text{Coal used/annum} \times \text{Calorific value}$$

$$= 10^7 \times 5000 = 5 \times 10^{10} \text{ kcal}$$

$$\text{Heat output} = \eta_{overall} \times \text{Heat of combustion}$$

$$= (0\cdot297) \times (5 \times 10^{10}) = 1485 \times 10^7 \text{ kcal}$$

$$\text{Units generated/annum} = 1485 \times 10^7/860 \text{ kWh}$$

$$\therefore \quad \text{Average load on station} = \frac{\text{Units generated / annum}}{\text{Hours in a year}} = \frac{1485 \times 10^7}{860 \times 8760} = \mathbf{1971\ kW}$$

Example 2.10. *A hydro-electric power station has a reservoir of area 2·4 square kilometres and capacity 5×10^6 m^3. The effective head of water is 100 metres. The penstock, turbine and generation efficiencies are respectively 95%,90% and 85%.*

(*i*) *Calculate the total electrical energy that can be generated from the power station.*

(*ii*) *If a load of 15,000 kW has been supplied for 3 hours, find the fall in reservoir level.*

Solution.

(*i*) Wt. of water available, W = Volume of reservoir × wt. of 1m^3 of water

$= (5 \times 10^6) \times (1000)$ kg $= 5 \times 10^9 \times 9{\cdot}81$ N

Overall efficiency, $\eta_{overall} = 0{\cdot}95 \times 0{\cdot}9 \times 0{\cdot}85 = 0{\cdot}726$

Electrical energy that can be generated

$$= W \times H \times \eta_{overall} = (5 \times 10^9 \times 9{\cdot}81) \times (100) \times (0{\cdot}726) \text{ watt-sec.}$$

$$= \frac{(5 \times 10^9 \times 9\cdot 81) \times (100) \times (0\cdot 726)}{1000 \times 3600} \text{ kWh} = \mathbf{9{,}89{,}175 \ kWh}$$

(*ii*) Let x metres be the fall in reservoir level in 3 hours.

$$\text{Average discharge/sec} = \frac{\text{Area of reservoir} \times x}{3 \times 3600} = \frac{2\cdot 4 \times 10^6 \times x}{3 \times 3600} = 222\cdot 2x \text{ m}^3$$

Wt. of water available/sec, $W = 222{\cdot}2x \times 1000 \times 9{\cdot}81 = 21{\cdot}8x \times 10^5$ N

Average power produced $= W \times H \times \eta_{overall}$

$= (21{\cdot}8x \times 10^5) \times (100) \times (0{\cdot}726)$ watts

$= 15{\cdot}84x \times 10^7$ watts $= 15{\cdot}84x \times 10^4$ kW

But kW produced = 15,000 (*given*)

∴ $15{\cdot}84x \times 10^4 = 15{,}000$

or $$x = \frac{15{,}000}{15\cdot 84 \times 10^4} = 0\cdot 0947 \text{ m} = \mathbf{9.47 \ cm}$$

Therefore, the level of reservoir will fall by 9·47 cm.

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* The total rainfall cannot be utilised as a part of it is lost by evaporation or absorption by ground. Yield factor indicates the percentage of rainfall available for utilisation. Thus 80% yield factor means that only 80% of total rainfall can be utilised.

Example 2.8. *Water for a hydro-electric station is obtained from a reservoir with a head of 100 metres. Calculate the electrical energy generated per hour per cubic metre of water if the hydraulic efficiency be 0·86 and electrical efficiency 0·92.*

Solution.

Water head, $H = 100$ m ; discharge, $Q = 1\ m^3/sec$; $\eta_{overall} = 0{\cdot}86 \times 0{\cdot}92 = 0{\cdot}79$

Wt. of water available/sec, $W = Q \times 1000 \times 9{\cdot}81 = 9810\ N$

Power produced $= W \times H \times \eta_{overall} = 9810 \times 100 \times 0{\cdot}79$ watts

$= 775 \times 10^3$ watts $= 775$ kW

$\therefore$ Energy generated/hour $= 775 \times 1 =$ **775 kWh**