


ENVC 24 : Energy and Environment

Part-2 : Nuclear Energy & Bioenergy

Vermont, USA

Cattenom, France

Trombay, India

AKB

Conventional energy sources

- **In Thermal power plant, work is available from mechanical energy released by fuel burning in a Thermodynamic cycle, which using electrical generator is converted. Depending on nature of working fluid, thermal power point are classified as → (a) Gas power cycle (GPC), (b) Vapour power cycle (VPC).**

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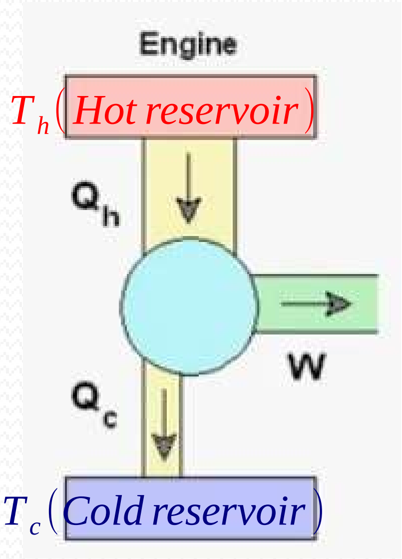
- Working fluid in GPC is mixture of air & gaseous combusted fuel product. In VPC, condensible vapour existing in liquid phase is the working fluid. Water is converted into steam in boiler using heat derived from coal. Steam flowing out from the boiler is made to rotate a turbine (imparting work), the steam is then made to flow into the condenser where water is regained giving out heat to the atmosphere – the water is forced back into the boiler with a feed pump.

Thermodynamics of Engines

- Heat engines ➡ convert energy into work.

$$\text{Efficiency}\ \eta = \frac{\textbf{Work Done}}{\textbf{Heat Absorbed}} = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h}.$$



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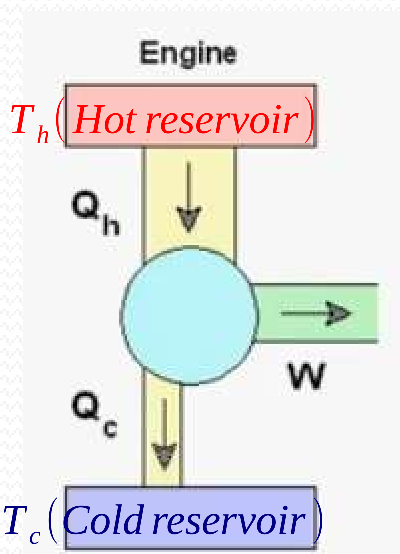
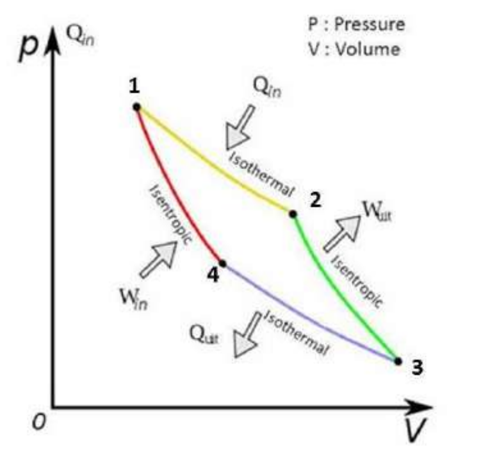
Carnot cycle : Provides an upper limit on the efficiency that any thermodynamic engine can achieve during the conversion of heat into work.





P-V Diagram of Carnot Cycle

indicator diagram

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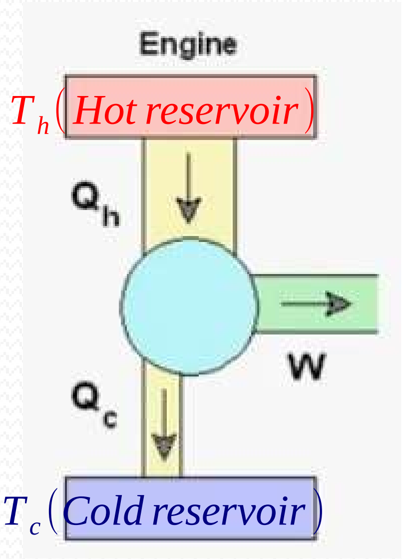
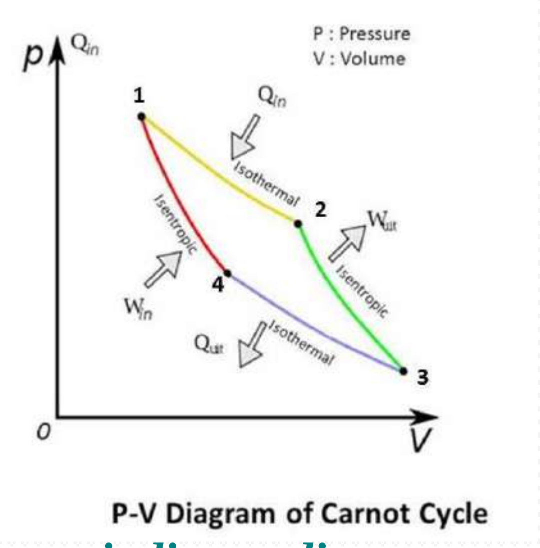
Carnot cycle : 1 → 2 reversible isothermal process : $PV = RT = \text{constant}.$





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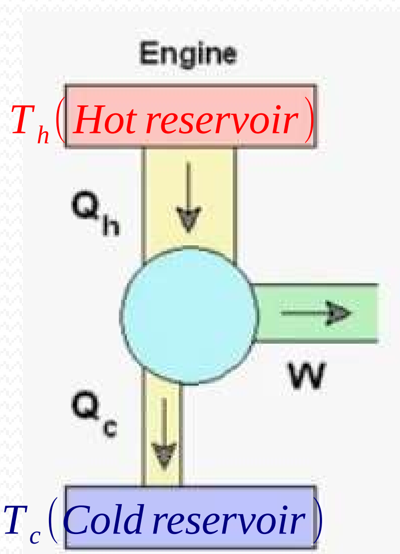

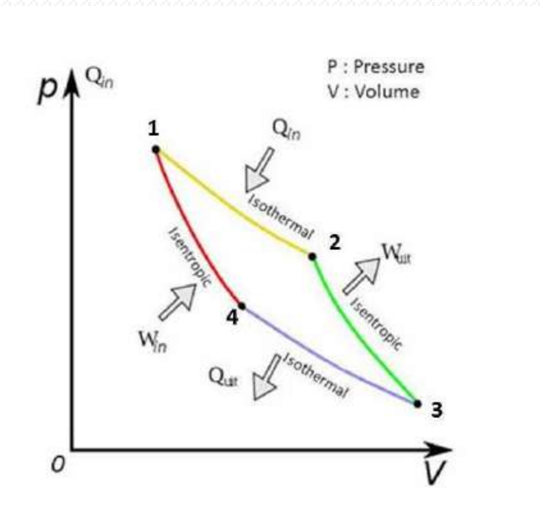

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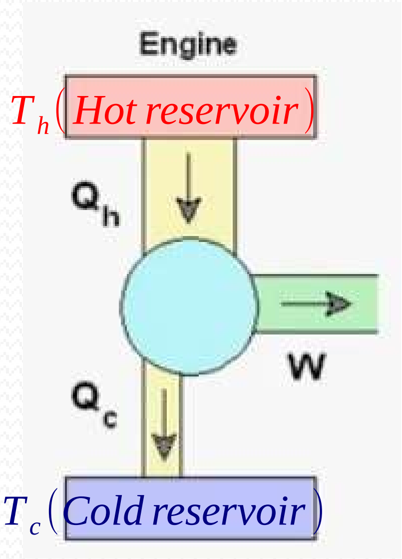
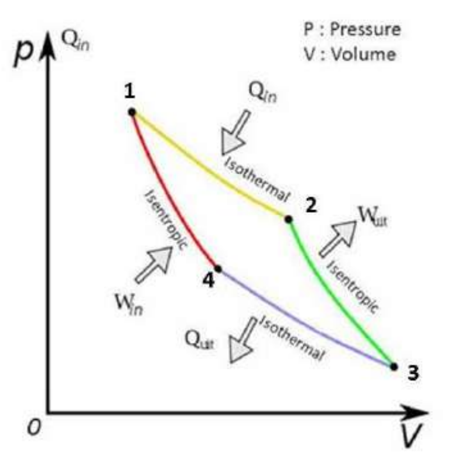
3 ► 4 reversible *isothermal* process: $PV = RT =$ constant.





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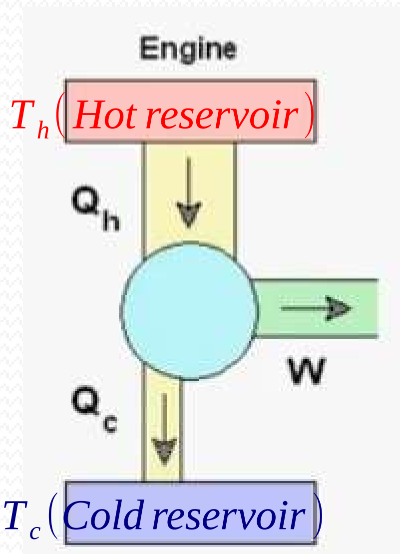

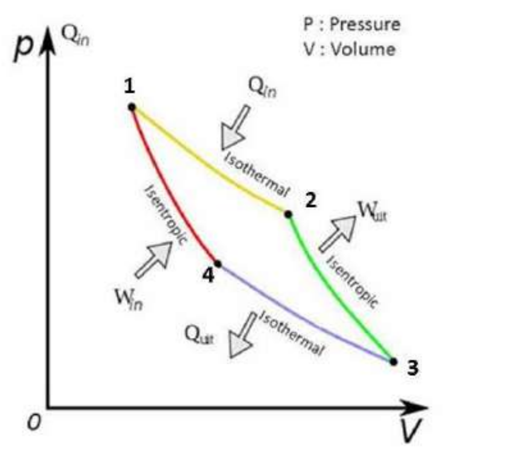

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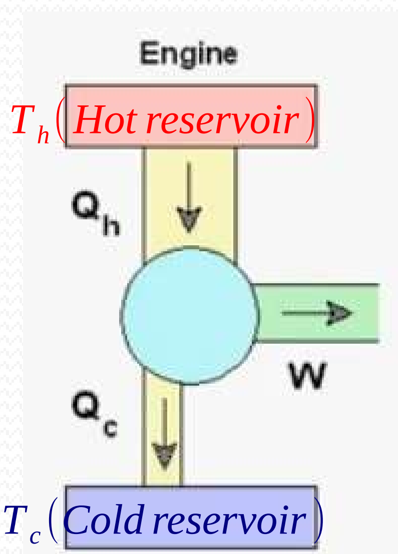
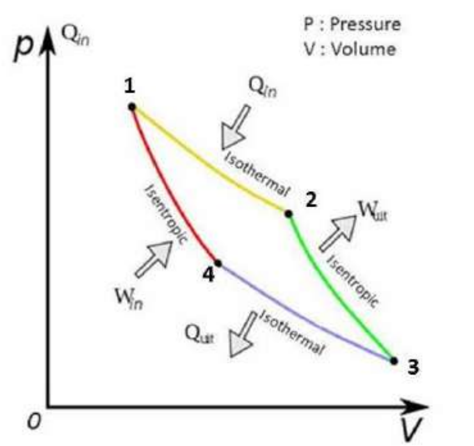
- Entropy $dS = \frac{dQ}{T}$ (as Q/T = constant, resulting to T.D. scale of temperature).





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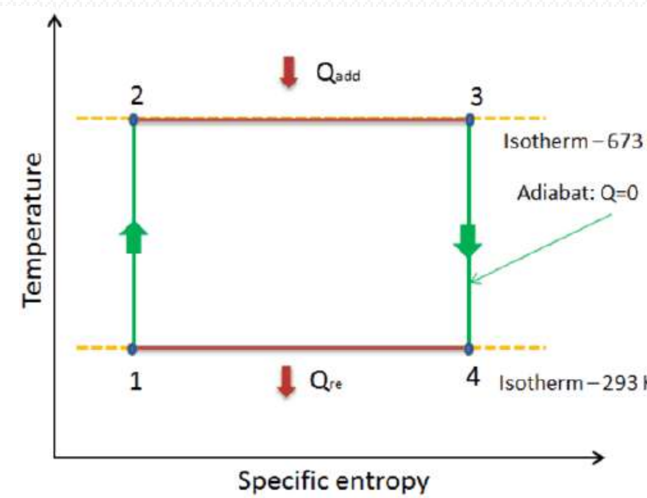

$$dS = \frac{dQ}{T}$$

AKB

Thermodynamics of Engines

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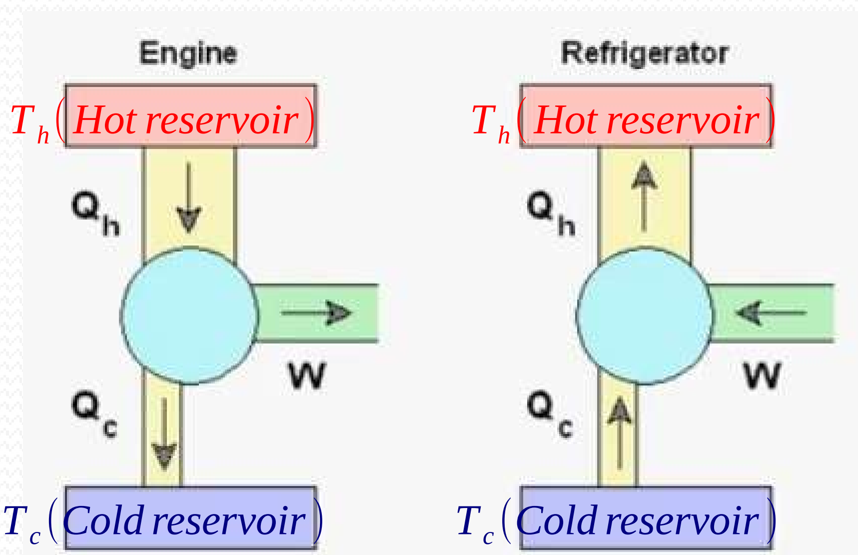

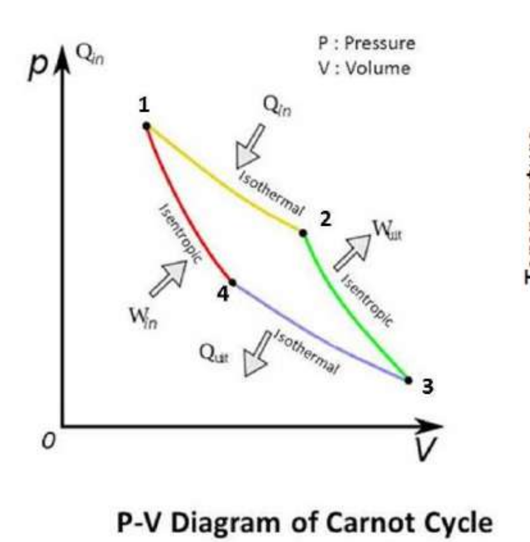

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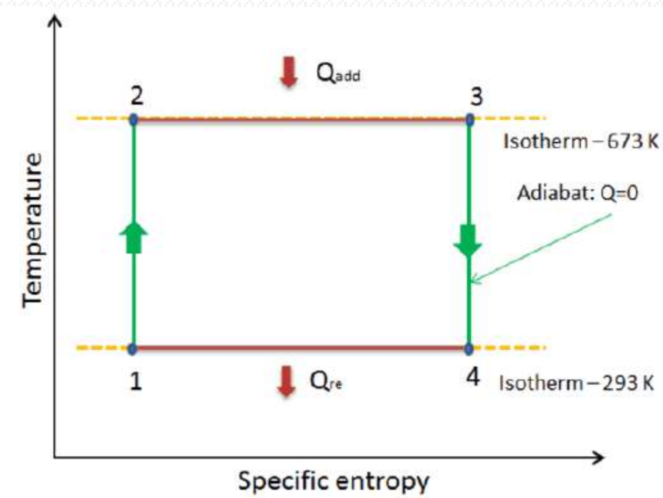

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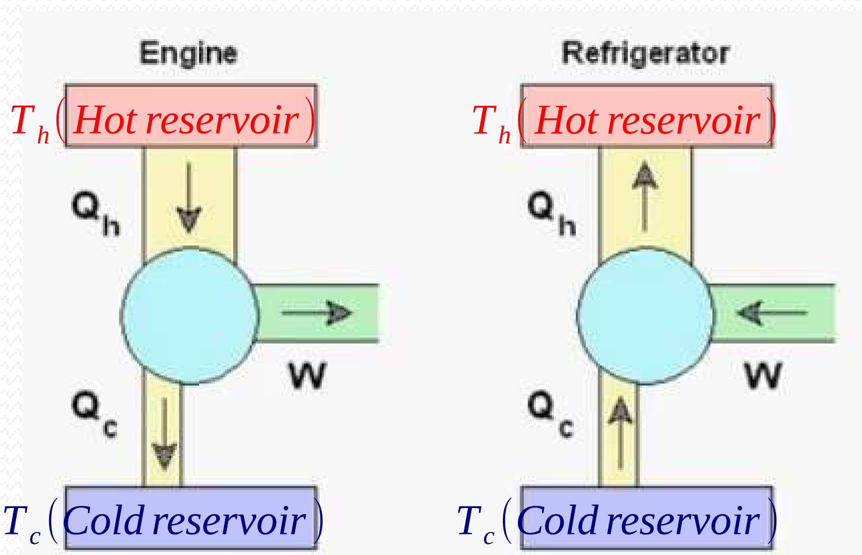
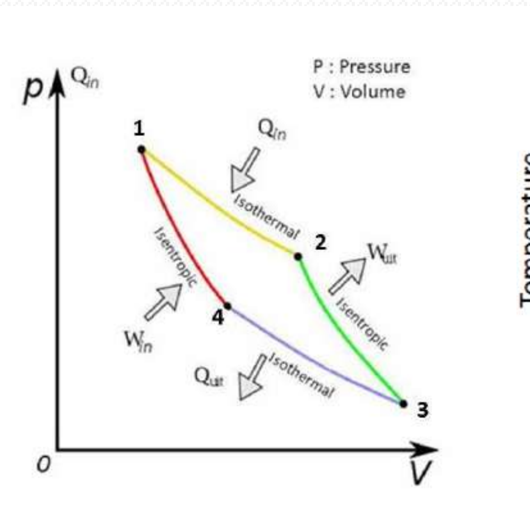
- Carnot's efficiency is ***independent*** of fuel/working substance and depends on hot and cold reservoir temperature only!





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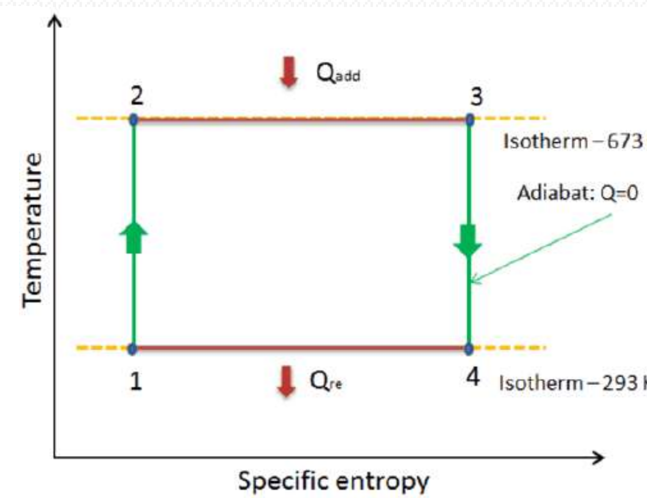

$$dS = \frac{dQ}{T}$$

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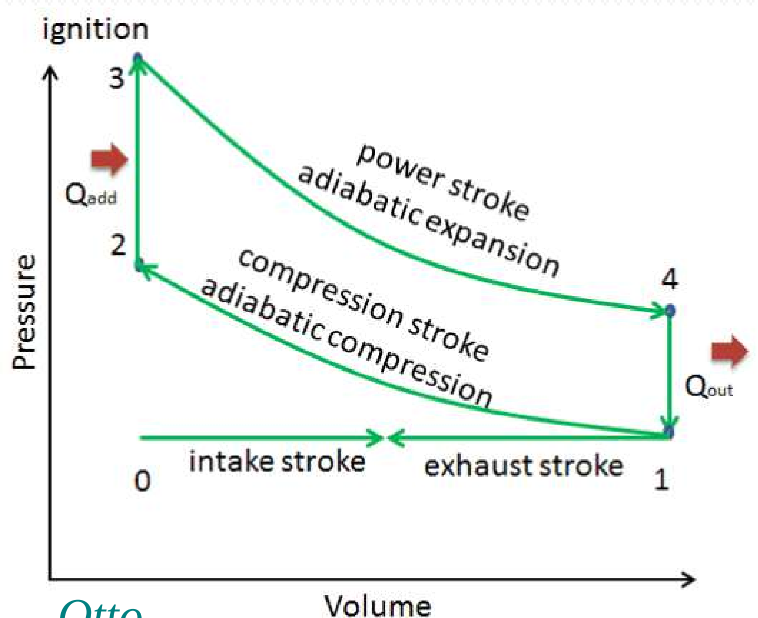
Otto, Diesel & Rankine cycle

- Ideal Carnot efficiency can be closely reached in Thermal power plants based on the **Rankine cycle** **(steam eng.)**, Otto cycle (petrol eng.) & **Diesel cycle** (diesel eng.).
- Reversible strokes ➡ Intake, Compression, Ignition/Combustion, Power, Valve exhaust & Exhaust stroke.

η ~ 67%.



Otto

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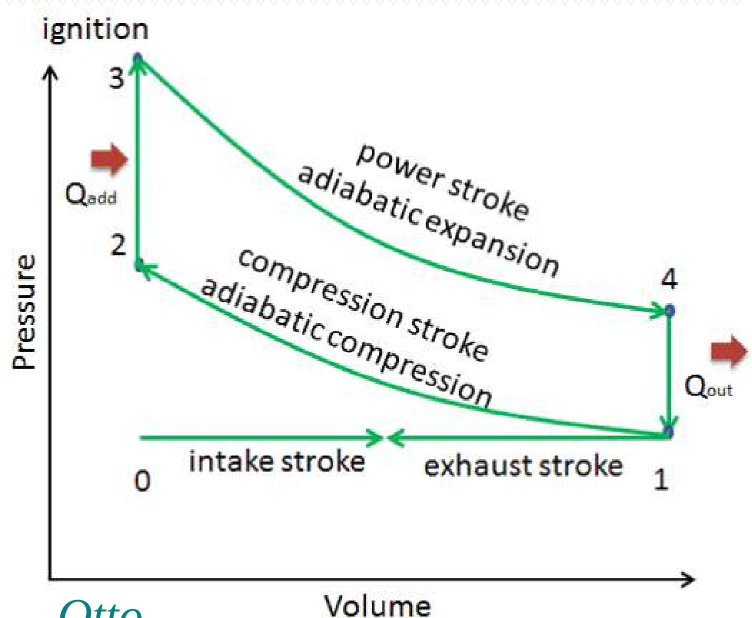
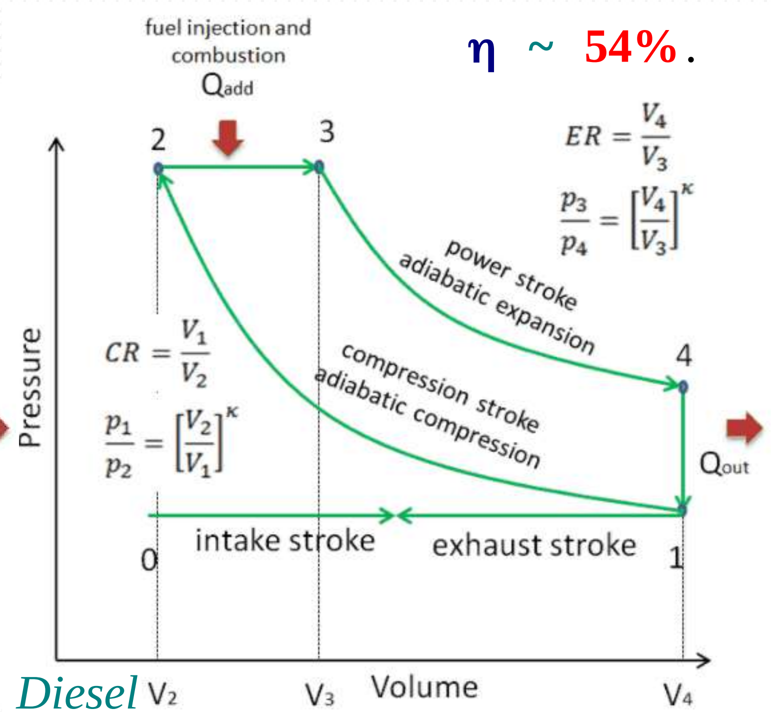


Otto

$\eta \sim$ **54%**.



Diesel

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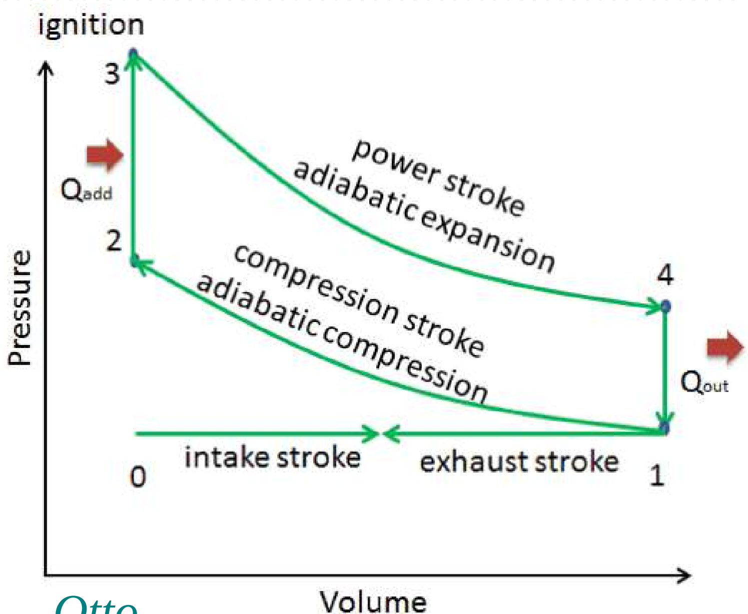
1 → 2 : low to high pressure (liquid)
2 → 3 : constant P heating (liquid → vapour)
3 → 4 : vapour expansion (P & T decrease)
4 → 1 : condensation @ constant P (liquid)

$\eta \sim$ **67%**.



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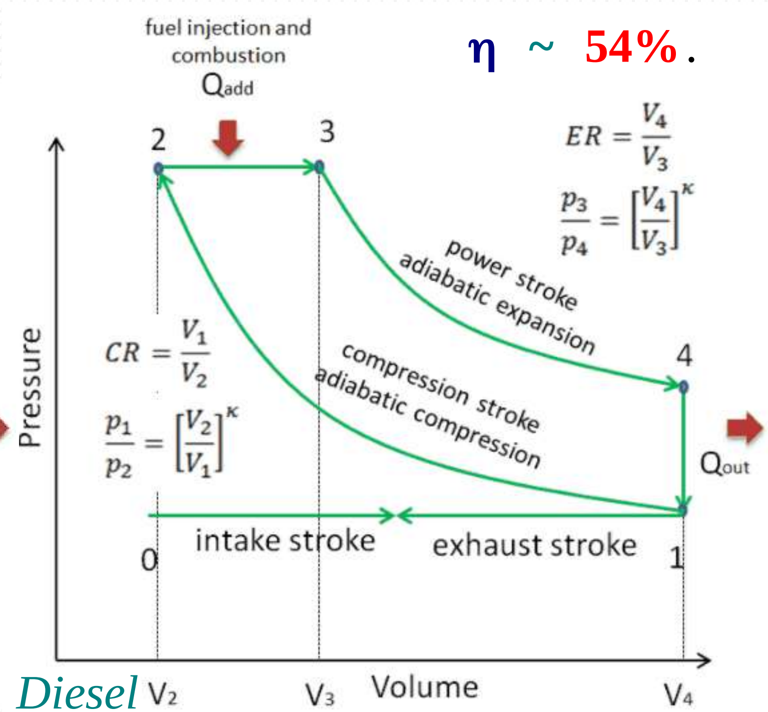
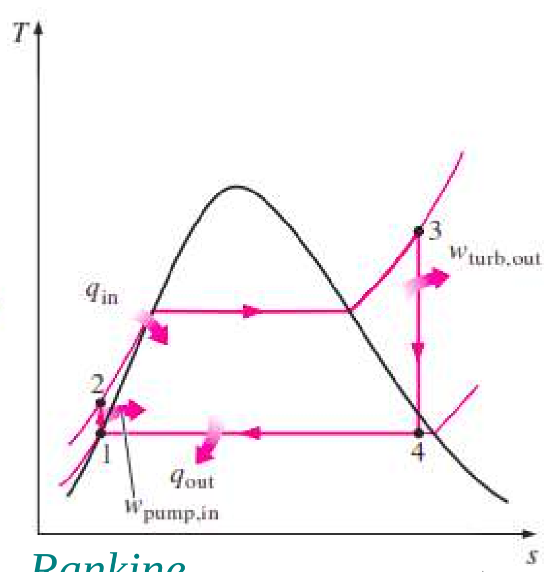


Diesel

$\eta \sim$ **50%**.



Rankine

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Efficiency Improvement

- Superheating, Reheating and Regenerative Heating are employed to improve the efficiency of a thermal power plant, where close to ideal Carnot efficiency can be reached. In contrast, nuclear power plant uses nuclear energy in a nuclear fission chain initiated by fissile mass (nuclear fuel).

Atoms & Chemical Bond

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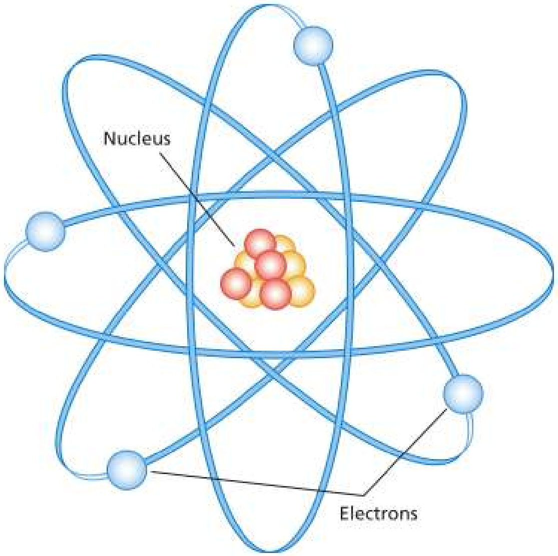
- Atoms are fundamental units (Electrons gyrating Nucleus, Planets gyrating Sun,...).

Bohr Model



Mass $m_p \sim m_n = 1800\, m_e$

Charge $m_p = +1, m_n = 0, m_e = -1$

$$m_p = 1.673\, x\, 10^{-27}\, kg$$

$$m_n = 1.675\, x\, 10^{-27}\, kg = 1\, \text{atomic mass unit}\, (amu)$$

$$m_e = 9.1\, x\, 10^{-31}\, kg$$

Atoms & Chemical Bond

- Chemical bonds form by bringing atoms from infinity to closest separation, so that total energy is negative (cohesive energy) = attractive force of negatively charged cloud of one atom with positive nuclear charge of other atom + repulsive force of overlapping negatively charged electron clouds & positively charged nucleus of two atoms.

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- Types of bond : (a) Ionic Bond

$[NaCl, KCl]$

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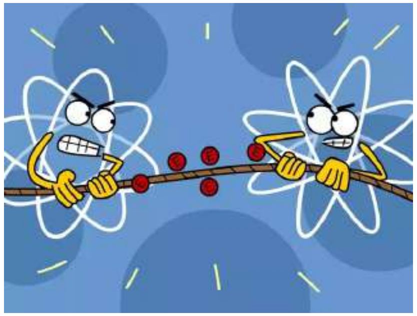
$[NaCl, KCl]$

$[F_2, CO_2, HCl]$



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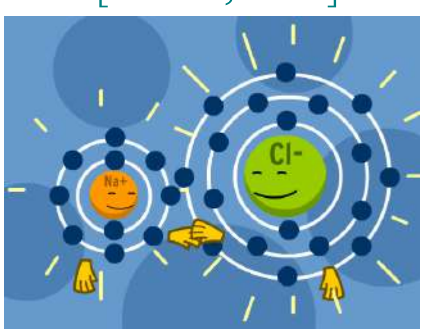

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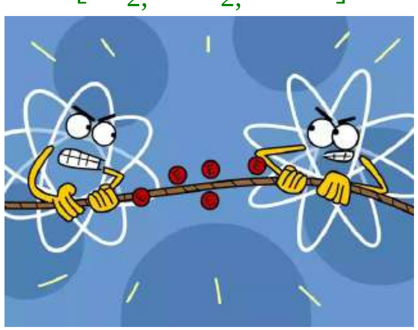

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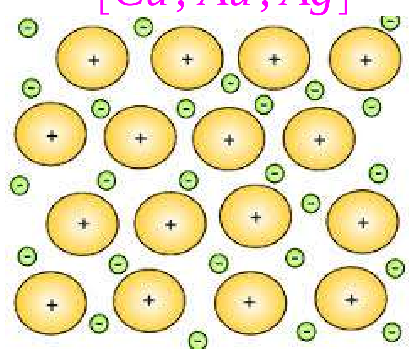

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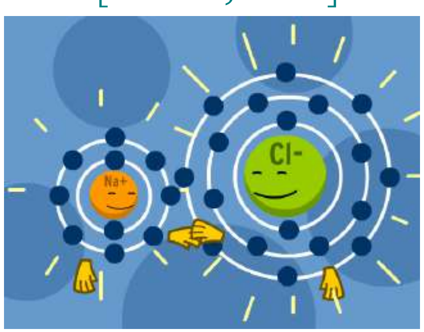

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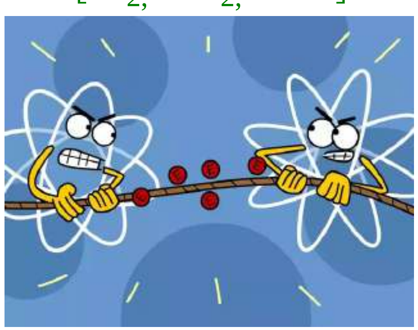

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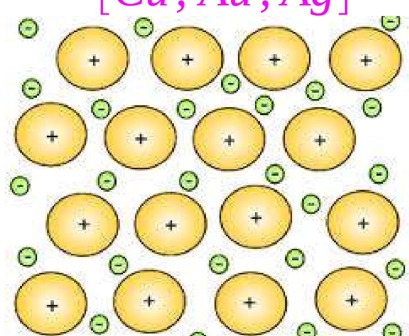
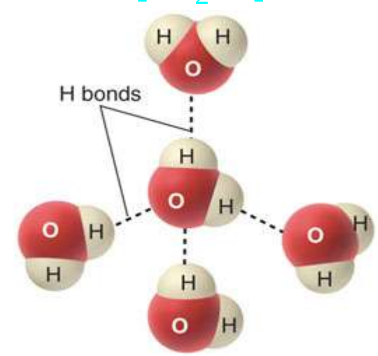


$[H_2O]$



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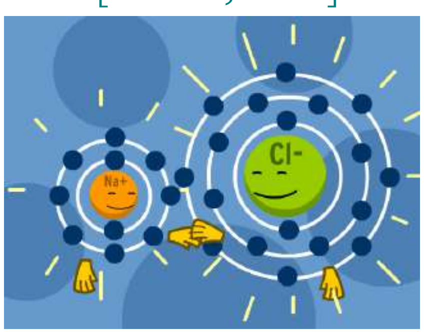

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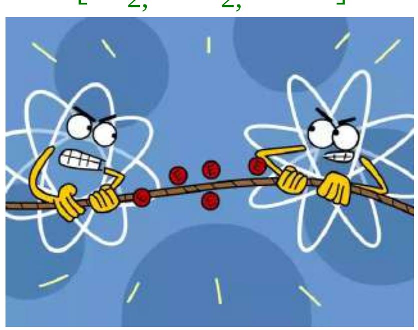

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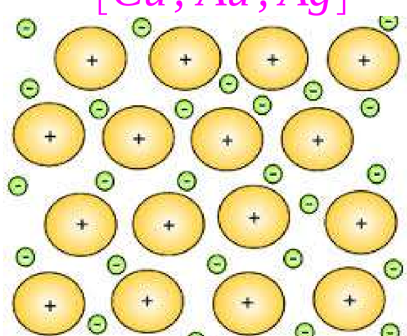

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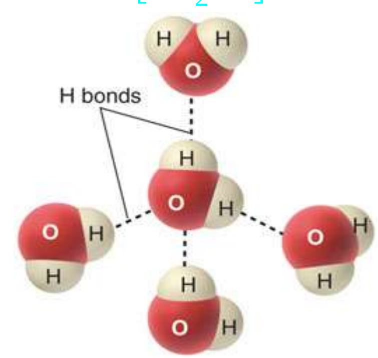
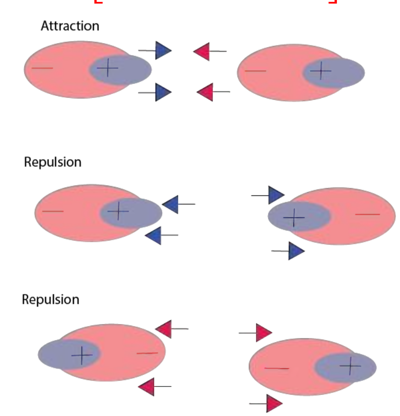


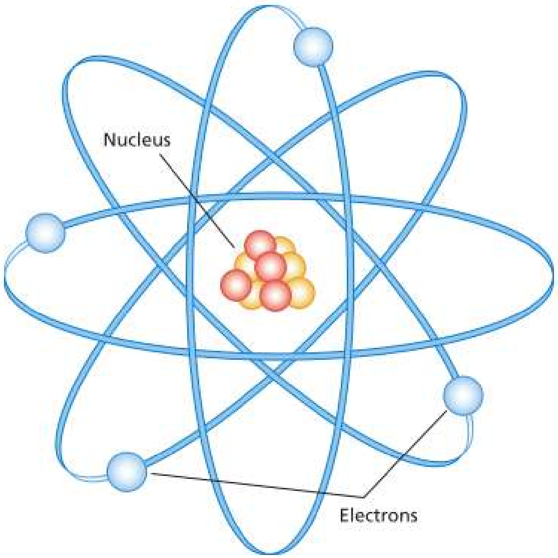
[most fluids]



What is Nuclear Energy?

- Atoms are fundamental units (Electrons gyrating Nucleus, Planets gyrating Sun,...).

Bohr Model



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Charge $m_p = +1, m_n = 0, m_e = -1$

- Neutron can change into proton by emitting an electron (β-particle) ➲ transmutation.

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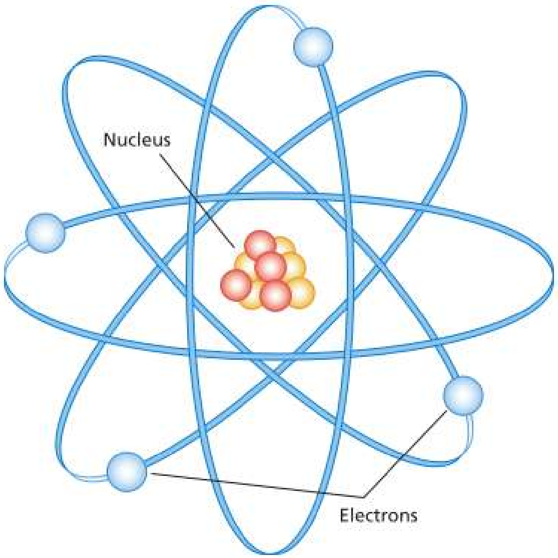

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- Neutron can change into proton by emitting an electron (β-particle) ➔ transmutation.
- Number of protons = atomic number (subscript). Same number of protons/electrons, different number of neutrons = different isotopes of same element.
- Proton + neutron = “nucleon”.

What is Nuclear Energy?

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- Radioactive materials, rather than coal, as sources of thermal energy by radioactive spontaneous disintegration of atomic nucleus.

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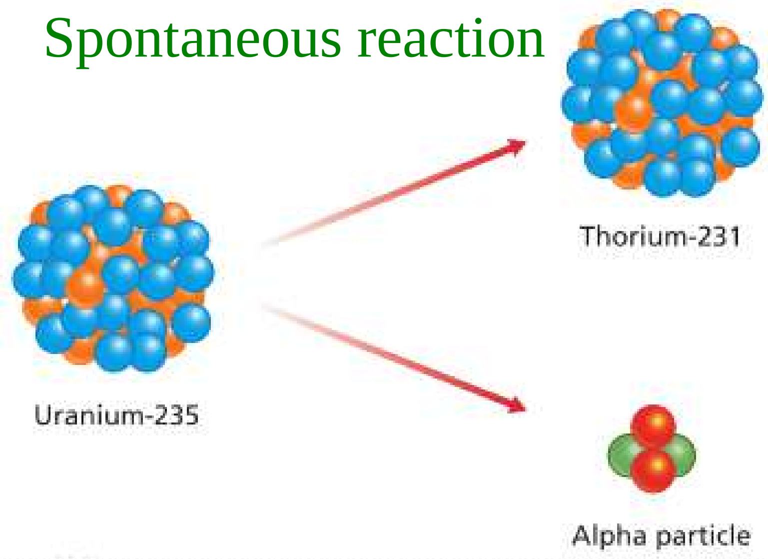
$$U_{92}^{235} \Rightarrow Th_{90}^{231} + He_2^4$$

Spontaneous reaction



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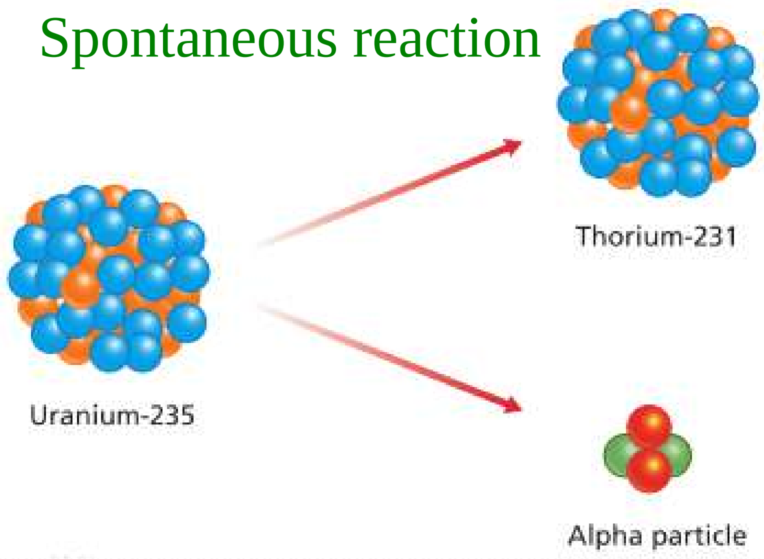
Conservation rules

$U_{92}^{235} \Rightarrow Th_{90}^{231} + He_2^4$

- Total protons + neutrons (mass no) = constant.
- Total electric charge = constant.
- Total energy of atoms = constant.

Spontaneous reaction



What is Nuclear Energy?

- Number of protons + neutrons = mass number (superscript). X_{A}^{M}
- Radioactive materials, rather than coal, as sources of thermal energy by radioactive spontaneous disintegration of atomic nucleus.

Conservation rules

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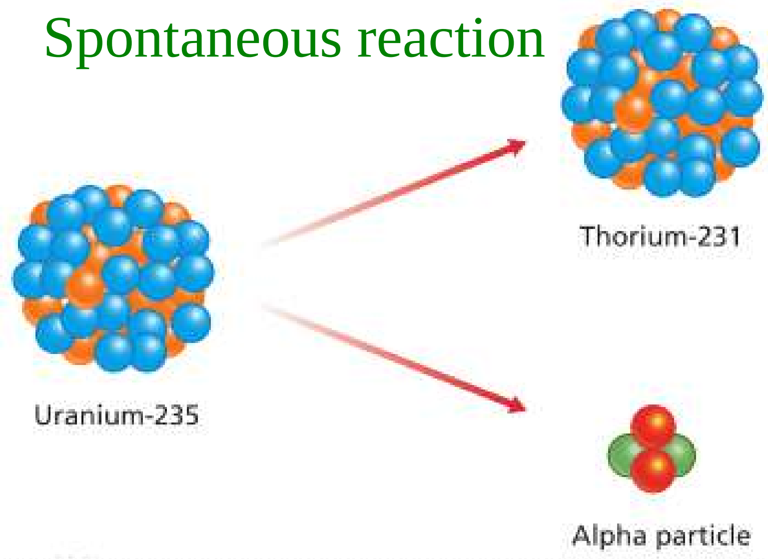

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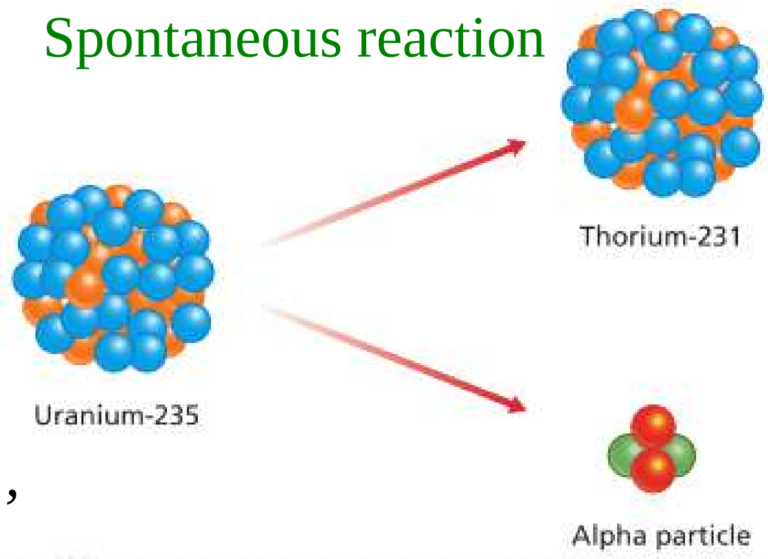

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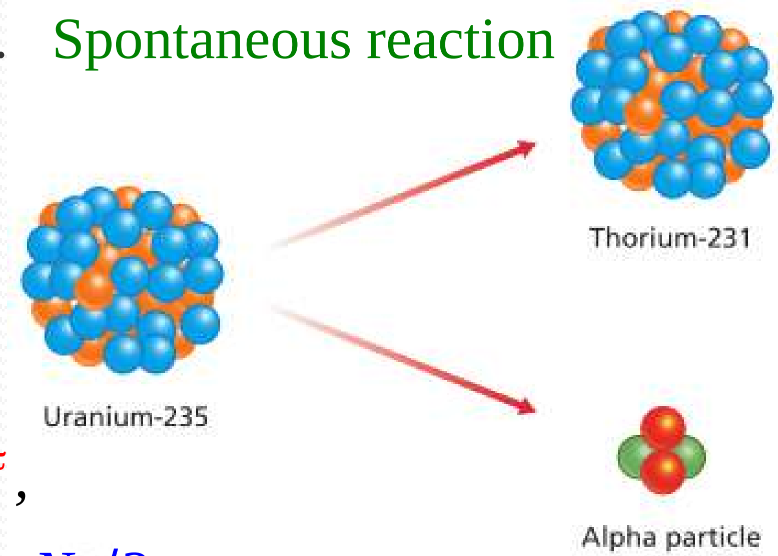

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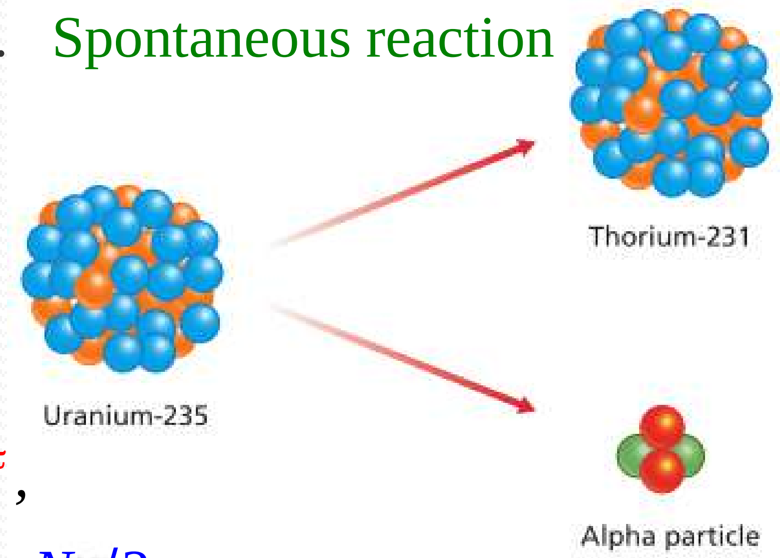

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- Example Kr_{36}^{85} ~ 11 years, Kr_{36}^{87} ~ 76 minutes.

AKB

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- In 4.5 billion years of lifespan of Earth, C_{6}^{14} (~ **5730 years**) is produced naturally, unlike U_{92}^{238} (~ **4.5 billion years**). So half of Uranium is present today.

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- **Principle of conservation of mass does not apply to nuclear reactions.** Difference between a chemical and a nuclear reaction is that, nuclear reaction involve making / breaking of very powerful bonds of protons and neutrons of atomic nucleus. By contrast, chemical reactions involve making/breaking of weaker bonds that bind atoms together within a molecule.

AKB

Missing Mass Phenomena

- "Missing mass phenomenon" ➔ When a group of protons and neutrons form an atomic nucleus, the mass of the nucleus will be less than the sum of the masses of its constituent parts. In the process, some of the mass of the particles in the nucleus was converted into the energy that binds the protons and neutrons of the nucleus together. Mass and energy can be converted into each other as $E=mc^2$. When nucleus is split, some of this binding energy is released and appears as thermal energy. The goal of a nuclear reactor is to release this thermal energy in a controlled way & then to harness it.

AKB

Activity & radioactivity

- In the process of radioactive decay, the activity R is measured by the number of atoms that disintegrate/second. $R = -\frac{dN}{dt}$. As $N(t) = N_0 e^{-\lambda t}$, $R = \lambda N = \lambda N_0 e^{-\lambda t}$.

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(a) Calculate the half life time & mean life time of a radioactive substance, whose decay constant is $4.28 x 10^{-4} / year$. (b) Suppose that half life is 5hrs. What will be its 1/3rd life time? (c) An element disintegrates for an interval of time equal to its mean life. What fraction of the element (i) remains & (ii) has disintegrated?

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  Therefore, fraction of element that remains $= \frac{1}{e}$.

  Fraction that has disintegrated $= 1 - \frac{1}{e} = \frac{e-1}{e}$.

AKB

Atomic Fission

- **Nuclear Fission** ➔ **Nuclear reactors are so designed to split atomic nuclei in a controlled way. The heat released during fission is then harnessed to do work.**

$n + U^{235}_{92} \rightarrow U^{*235}_{92}$

A view of the superconducting magnets at Brookhaven's Relativistic Heavy Ion Collider. These large machines are used to obtain insight into atomic structure. *(Brookhaven National Laboratory)*

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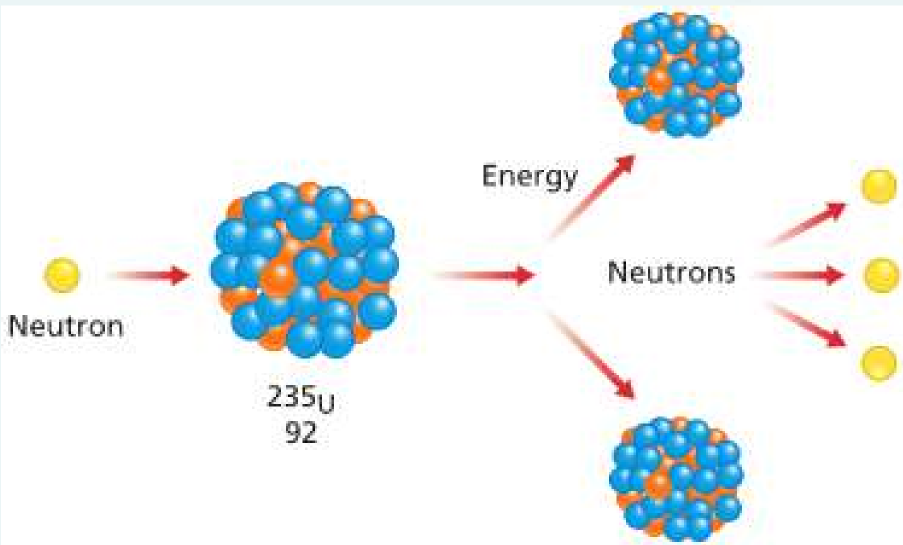

3 neutrons generate more chain reaction till radioactive isotopes decay to non-radio-active isotopes and heat generation stops. Depending on the produced atoms, fission can take minutes/days/weeks/centuries/ millennia. So one cannot turn-off a nuclear reactor like a light-bulb. Existent technologies can quickly “soak up” the free neutrons within the reactor, the products of the fission reaction continue to generate thermal energy as a result of radioactive decay.

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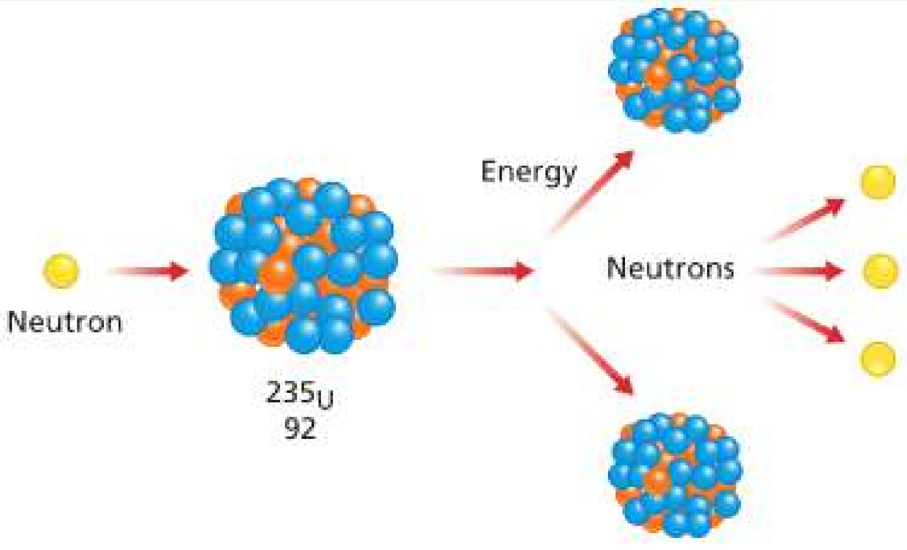

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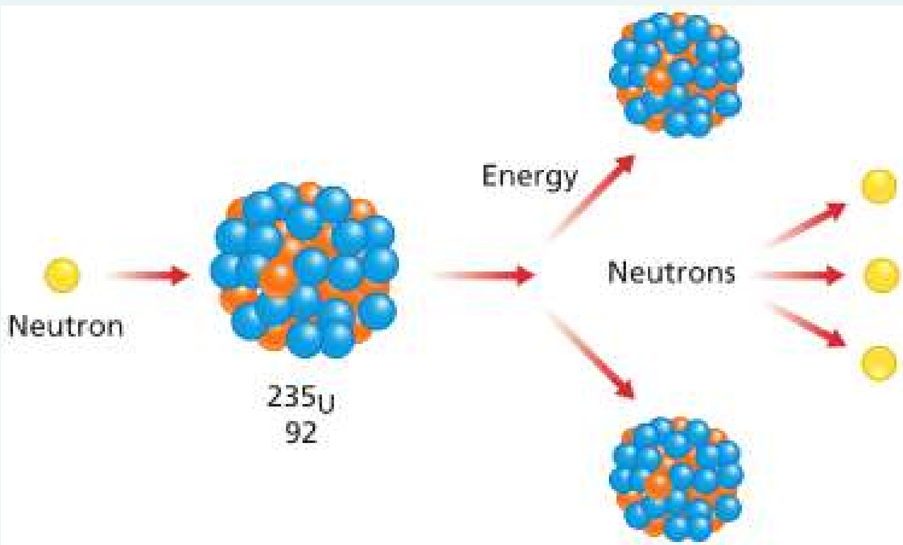

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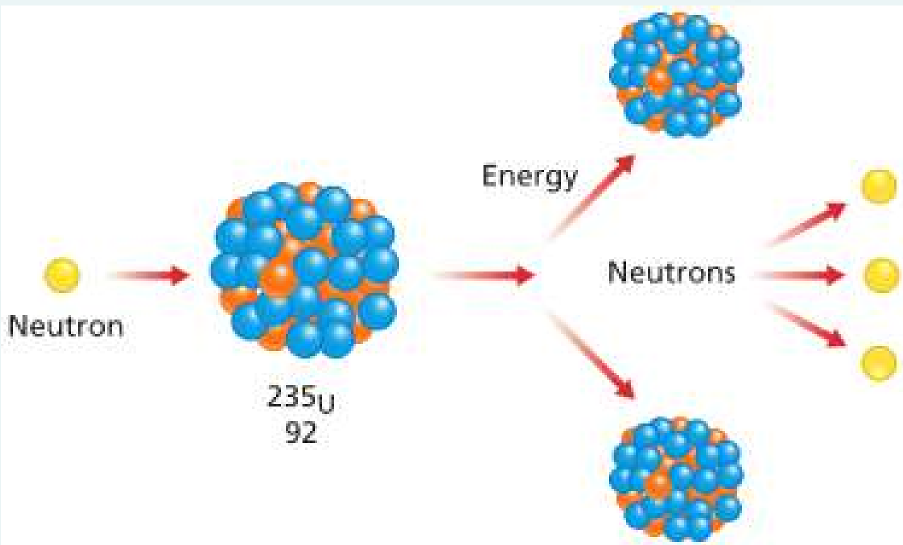

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Breeder reactors produce more fuel (Plutonium) than consumed Uranium-235

AKB

Radioactive Series

Most of the radioactive nuclides found in nature are members of **4** radioactive series. 1st member is called the *parent*, the intermediate members the *daughters* and final stable member is called the *end-product*. The series are,

Uranium Series

Actinium Series

Thorium Series

Neptunium Series

- $\alpha - decay$ reduces the mass number of a nucleus by 4. Thus, the nuclides whose mass number are given by A=**4n** (n=integer) can decay into each other in descending order of mass number 4n series members. Similarly, radioactive nuclides whose mass numbers obey the relation A=**4n+1** belong to (4n+1)series, A=**4n+2** belong to (4n+ 2)series, A=**4n+3** belong to (4n+3)series respectively.

Radioactive Series

Mass Number	Series	Parent	Half-life in years	Stable end-product
4n	Thorium	Th_{90}^{232}	1.39×10^{10}	Pb_{82}^{208}
4n + 1	Neptunium	Np_{93}^{237}	2.25×10^{6}	Bi_{82}^{209}
4n + 2	Uranium	U_{92}^{238}	4.51×10^{9}	Pb_{82}^{206}
4n + 3	Actinium	U_{92}^{235}	7.07×10^{8}	Pb_{82}^{207}

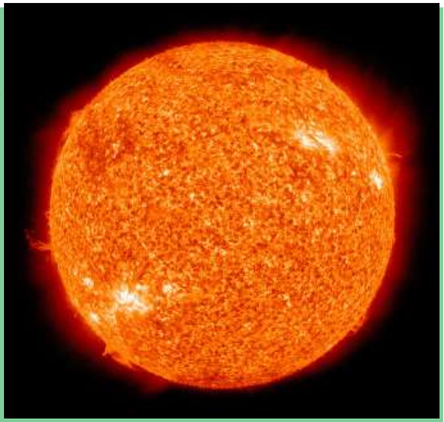
- End product of Uranium Series A=(4n+2) : Pb^{206} or Pb^{207} or Pb^{208} ??

  While $4n+2 \neq 207, 4n+2 \neq 208$ for any integer n, only for n=51, $4n+2=206$.

  So Pb^{206} will be the end product.

AKB

- Nuclear Fusion ➔ Reaction in which two (more) atomic nuclei come close to form one (more) different atomic nuclei and subatomic particles (neutrons or protons). Binding energy is released. Sun produces energy by nuclear fusion of 620 million metric tons of hydrogen nuclei into helium in each second.



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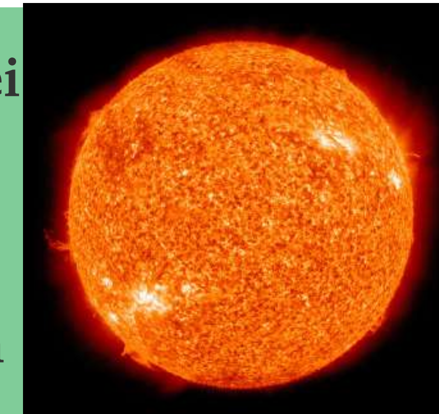

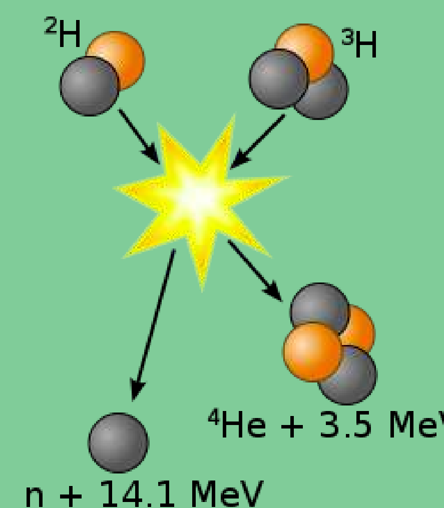

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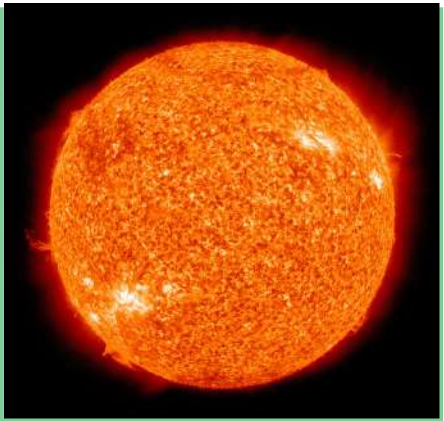
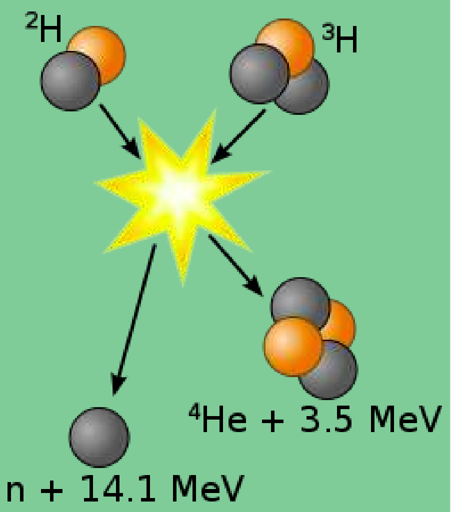
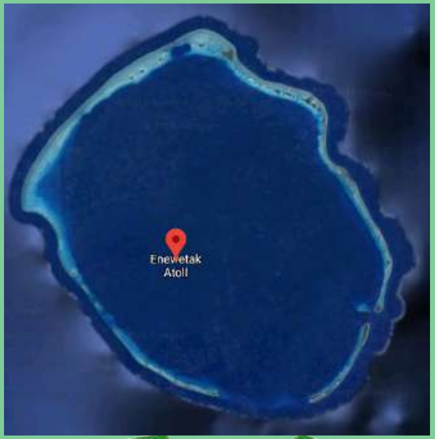
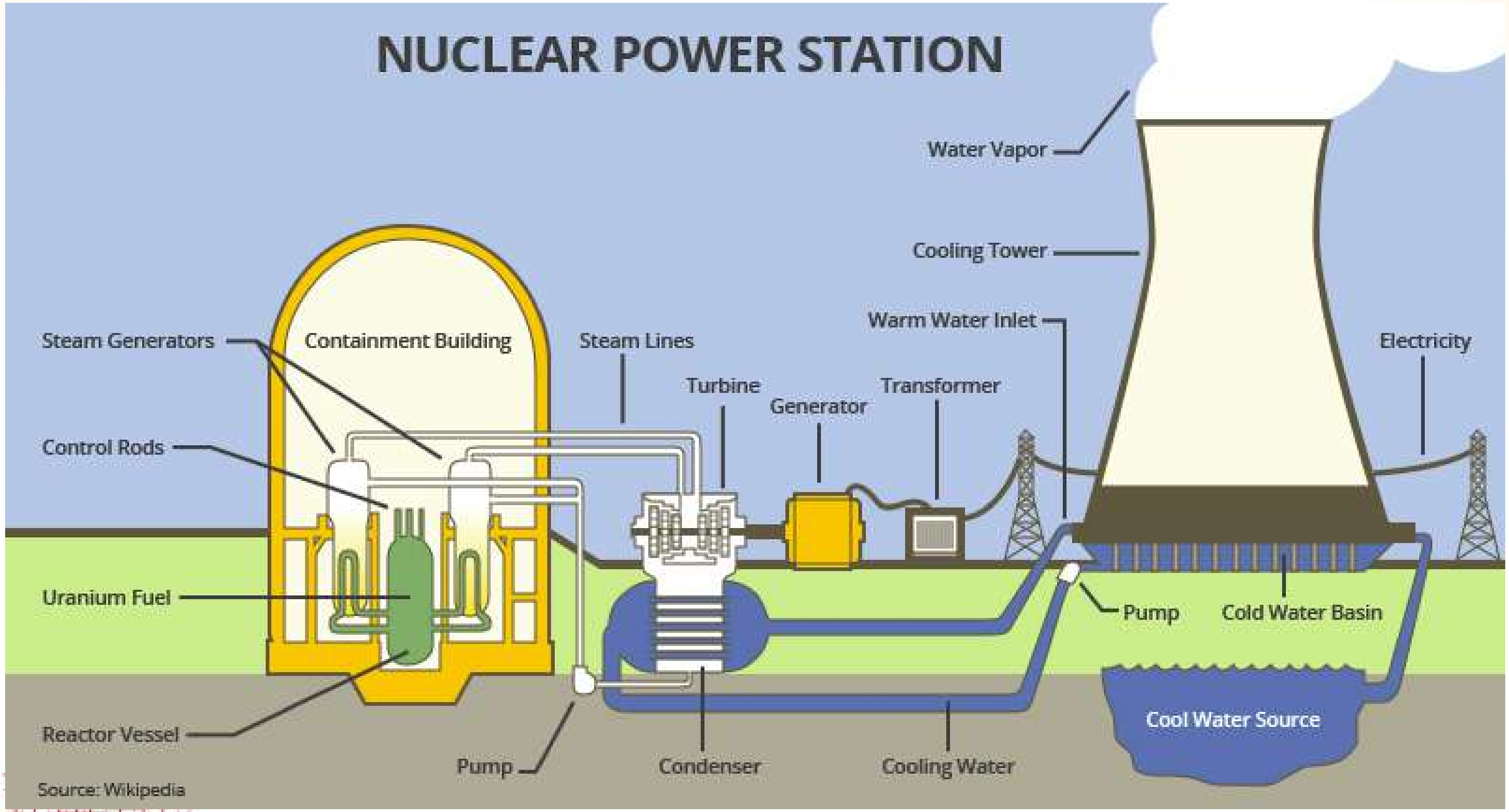
- Thermonuclear fusion test ➡ Ivy mike Hydrogen Bomb (1952).



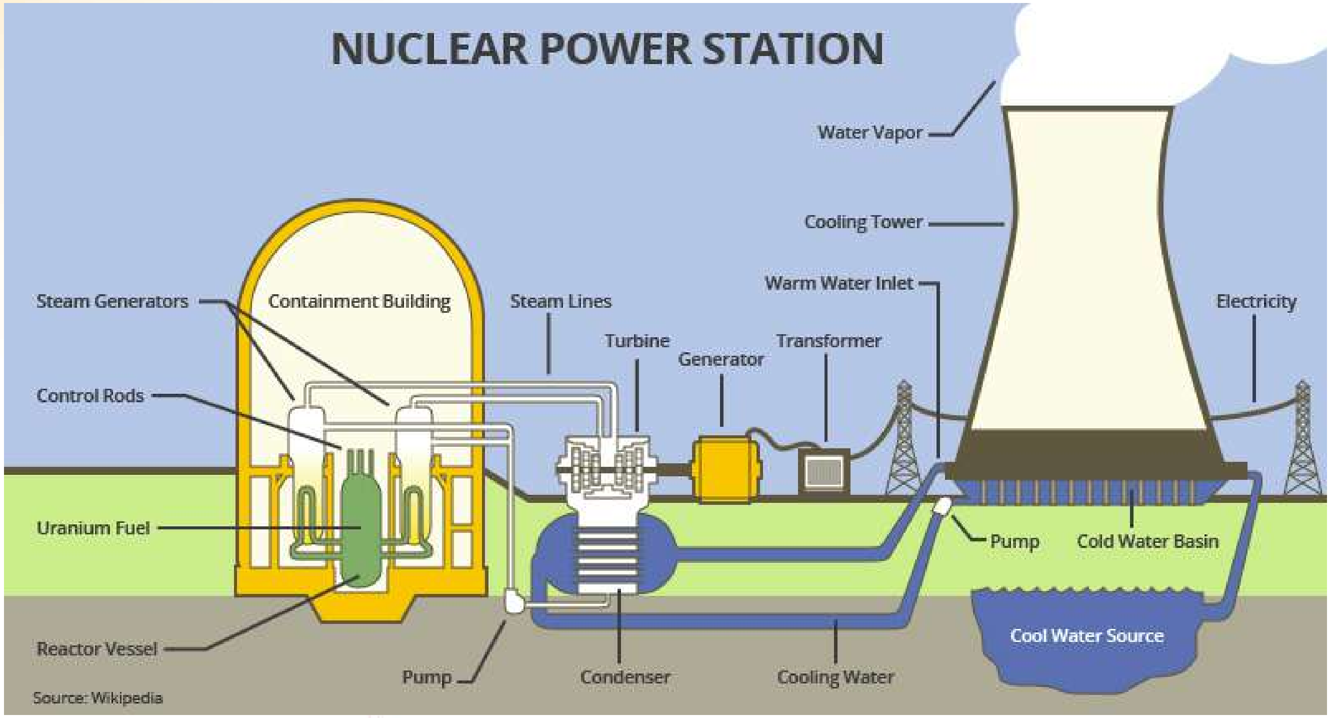






- Control rods control the fission rate of Uranium/Plutonium. They are composed of Boron/Silver/Indium/Cadmium capable of absorbing many neutrons without themselves fissioning. Because these elements have different capture crosssection for neutrons of varying energies, composition of control rods must be designed for the reactor's neutron spectrum. Boiling water reactors (BWR), Pressurized Water Reactors (PWR) and Heavy Water Reactors (HWR) operate with thermal neutrons, while Breeder Reactors (BR) operate with fast neutrons.

AKB



NUCLEAR POWER STATION
Water Vapor
Cooling Tower
Warm Water Inlet
Steam Generators
Containment Building
Steam Lines
Turbine
Generator
Transformer
Electricity
Control Rods
Uranium Fuel
Pump
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Cool Water Source
Reactor Vessel
Pump
Condenser
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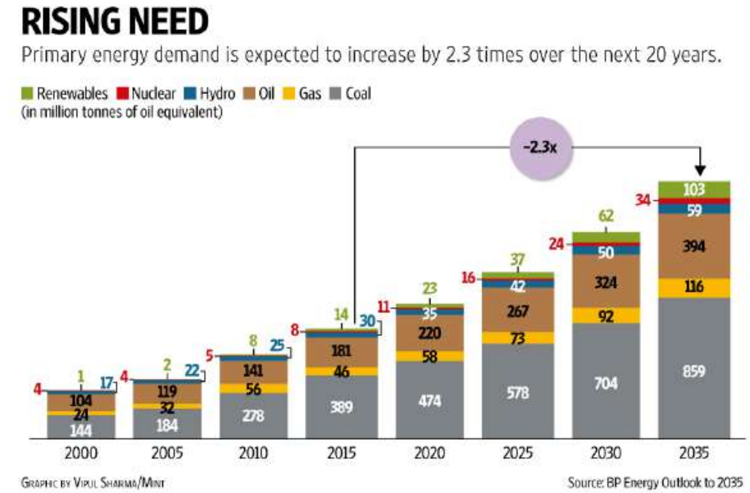
Source: Wikipedia



RISING NEED
Primary energy demand is expected to increase by 2.3 times over the next 20 years.
Renewables Nuclear Hydro Oil Gas Coal
(in million tonnes of oil equivalent)
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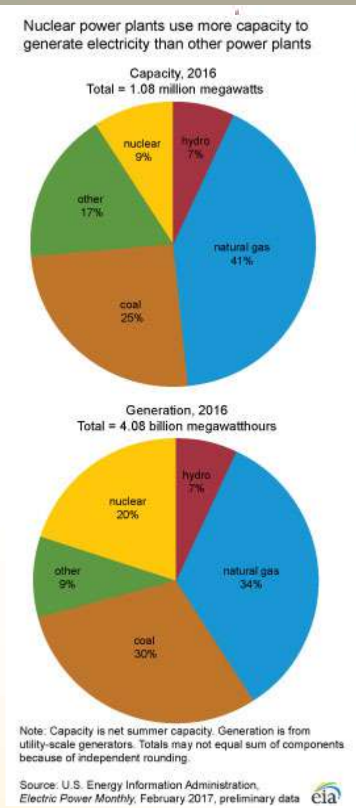
2000: 4 1 17 104 24 144
2005: 4 2 22 119 32 184
2010: 5 8 25 141 56 278
2015: 8 14 30 181 46 389
2020: 11 23 35 220 58 474
2025: 16 37 42 267 73 578
2030: 24 62 50 324 92 704
2035: 34 103 59 394 116 859
Graphic by Vipul Sharma/Mint
Source: BP Energy Outlook to 2035



Nuclear power plants use more capacity to generate electricity than other power plants
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nuclear 9%
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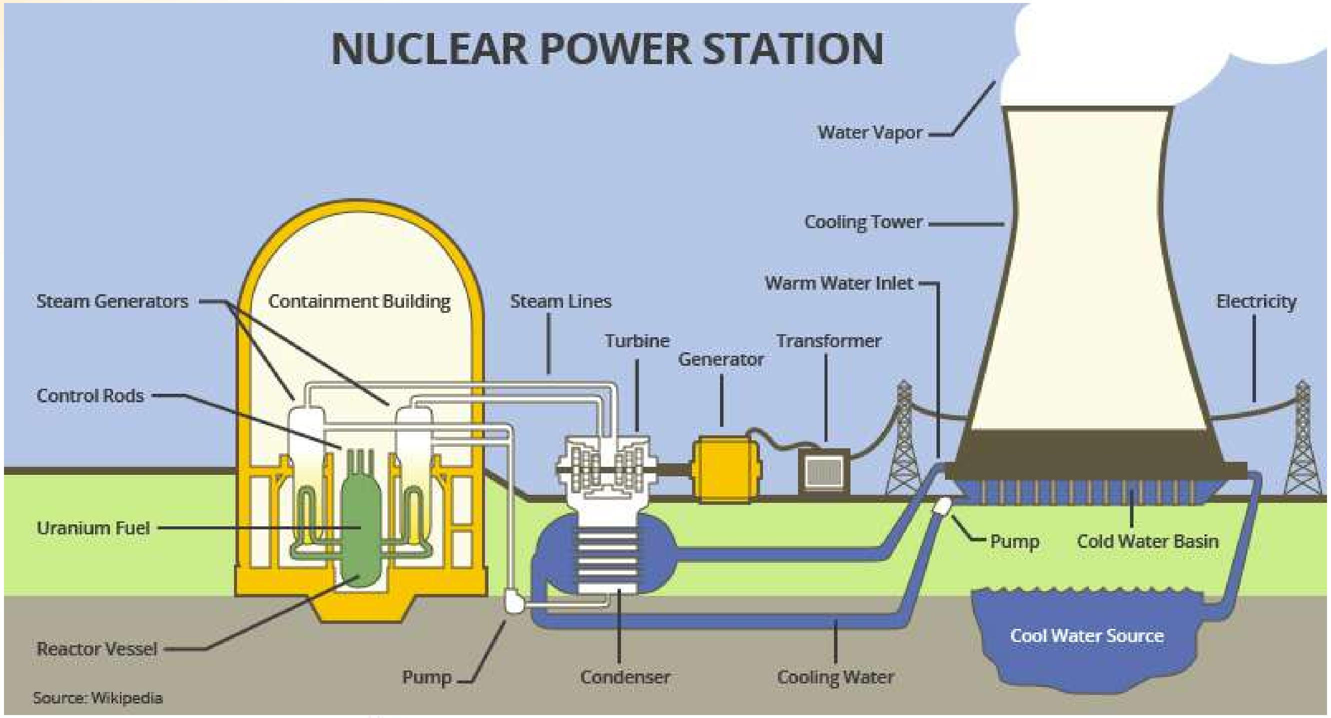
Source: U.S. Energy Information Administration, Electric Power Monthly, February 2017, preliminary data
eia

AKB



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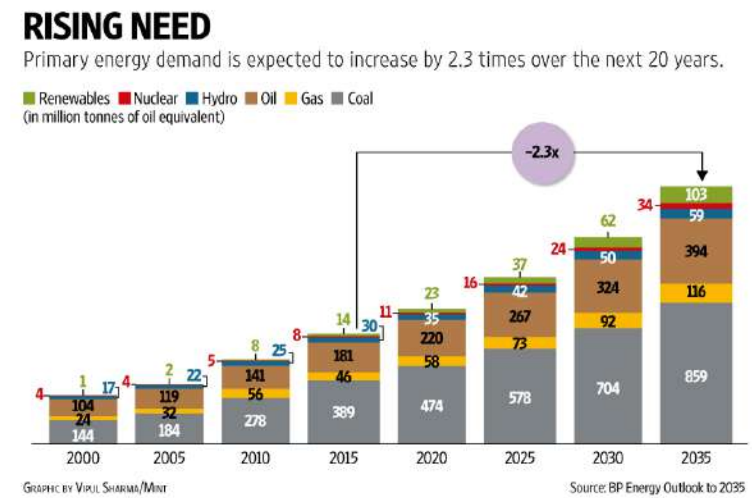
Source: Wikipedia



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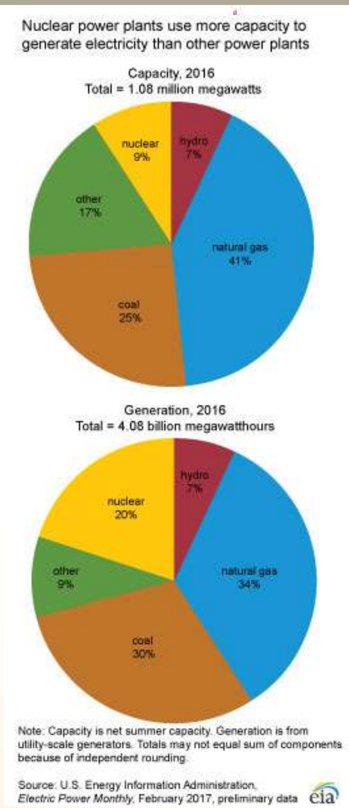

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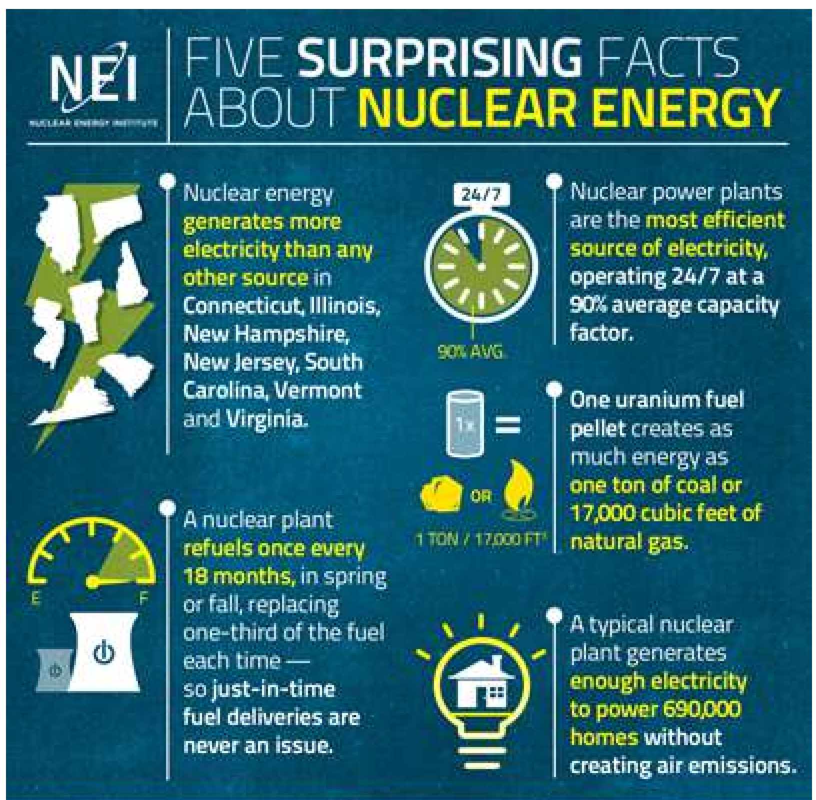
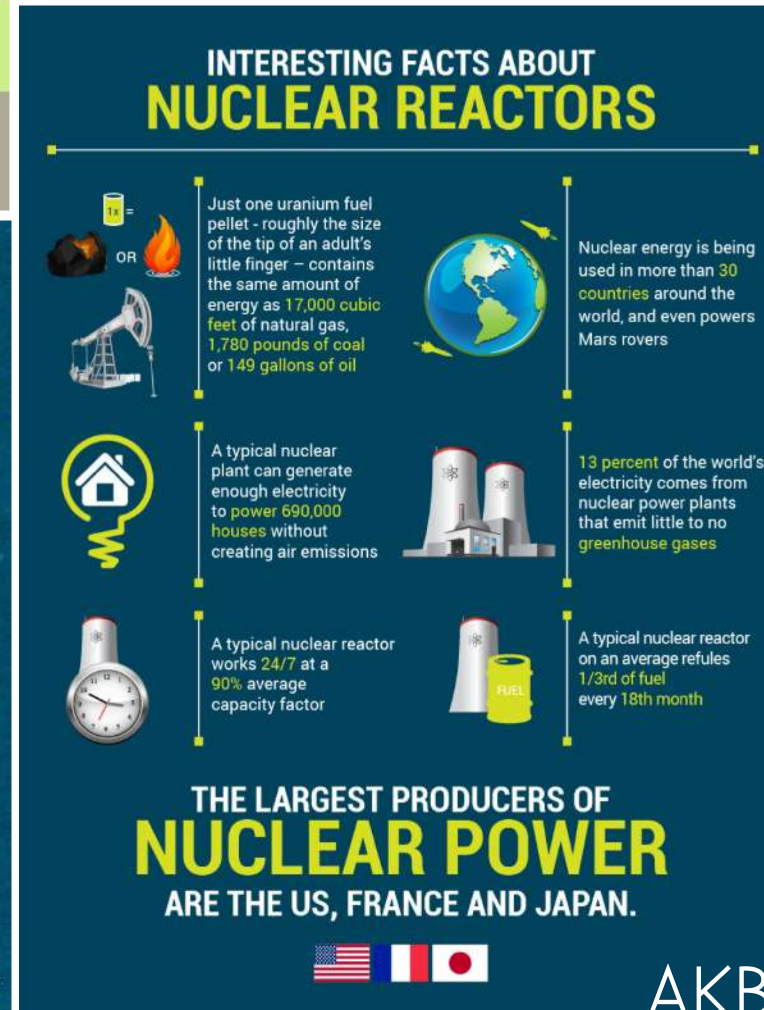


NEI
NUCLEAR ENERGY INSTITUTE
FIVE SURPRISING FACTS ABOUT NUCLEAR ENERGY
Nuclear energy generates more electricity than any other source in Connecticut, Illinois, New Hampshire, New Jersey, South Carolina, Vermont and Virginia.
24/7
90% AVG.
Nuclear power plants are the most efficient source of electricity, operating 24/7 at a 90% average capacity factor.
1x =
OR
1 TON / 17,000 FT³
One uranium fuel pellet creates as much energy as one ton of coal or 17,000 cubic feet of natural gas.
E F
A nuclear plant refuels once every 18 months, in spring or fall, replacing one-third of the fuel each time — so just-in-time fuel deliveries are never an issue.
A typical nuclear plant generates enough electricity to power 690,000 homes without creating air emissions.



INTERESTING FACTS ABOUT NUCLEAR REACTORS
1x =
OR
Just one uranium fuel pellet - roughly the size of the tip of an adult's little finger – contains the same amount of energy as 17,000 cubic feet of natural gas, 1,780 pounds of coal or 149 gallons of oil
Nuclear energy is being used in more than 30 countries around the world, and even powers Mars rovers
A typical nuclear plant can generate enough electricity to power 690,000 houses without creating air emissions
13 percent of the world's electricity comes from nuclear power plants that emit little to no greenhouse gases
A typical nuclear reactor works 24/7 at a 90% average capacity factor
FUEL
A typical nuclear reactor on an average refuels 1/3rd of fuel every 18th month
THE LARGEST PRODUCERS OF NUCLEAR POWER ARE THE US, FRANCE AND JAPAN.

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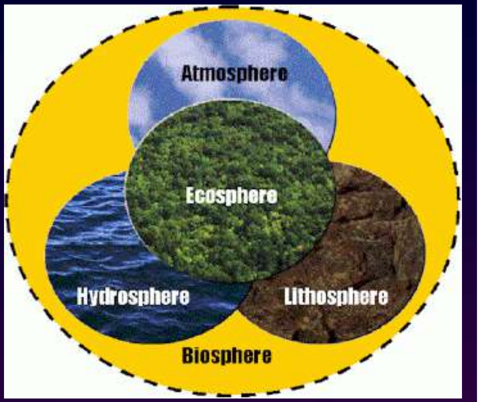
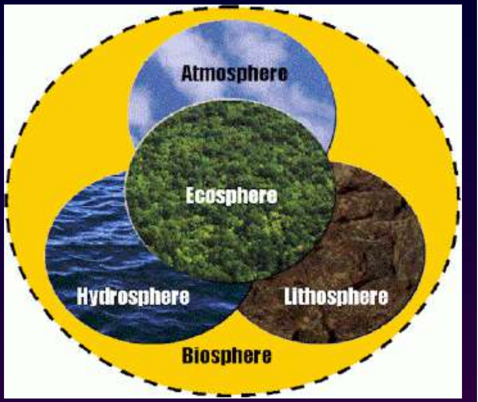
Carbon Cycle



- **Biochemical exchange between reservoirs: atmosphere, biosphere, soil (pedosphere), ocean, burial in sediments (source of fossil fuels), earth crust (lithosphere, limestone/rocks).**

Carbon Cycle



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AKB

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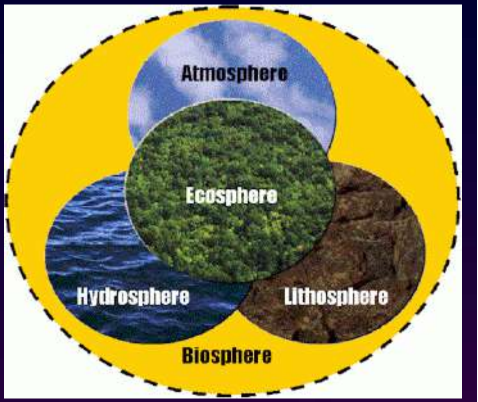

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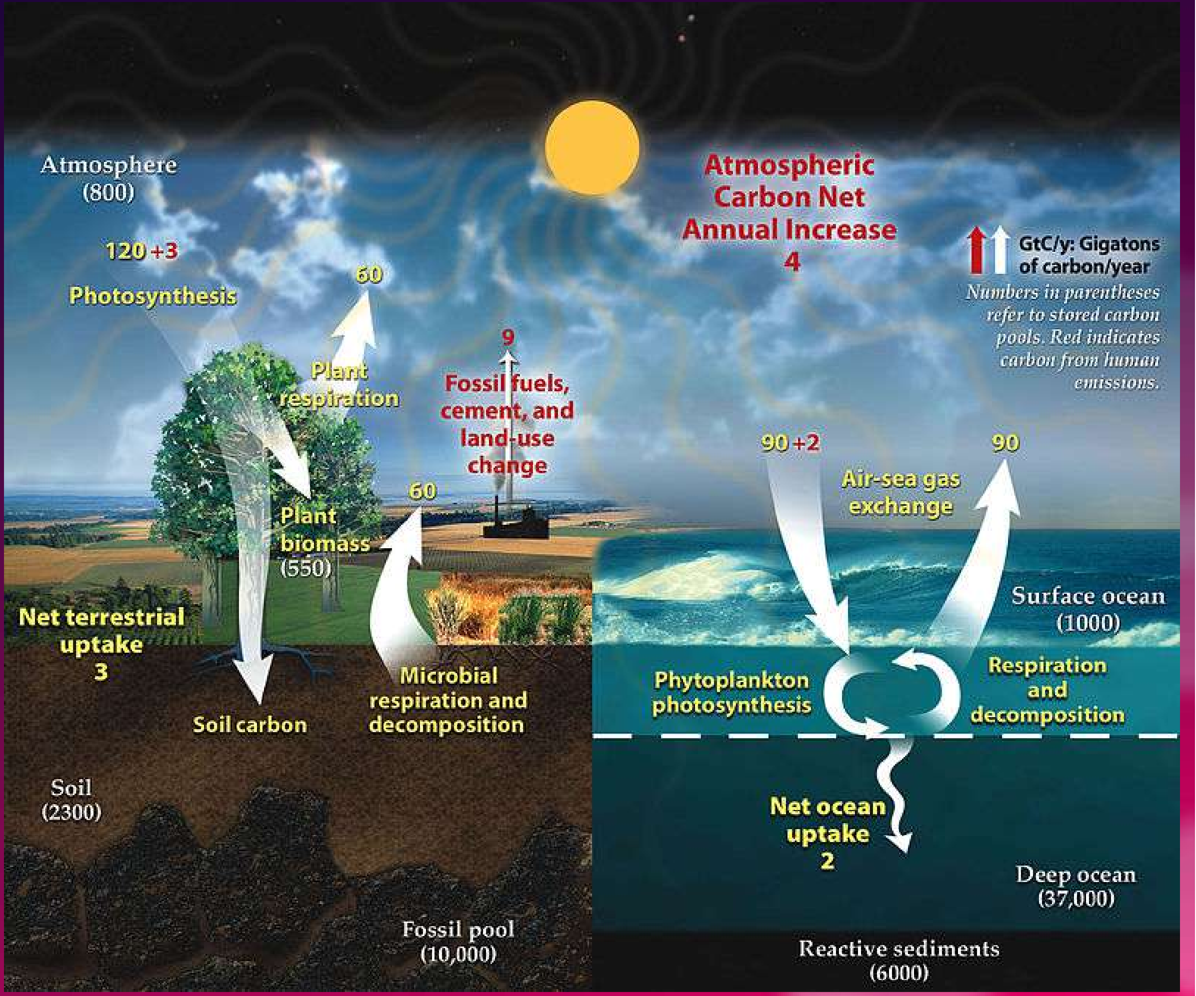
[GtC = Gigatonne Carbon $\left(10^{9}\right)$
PtC = Petatonne Carbon $\left(10^{15}\right)$]



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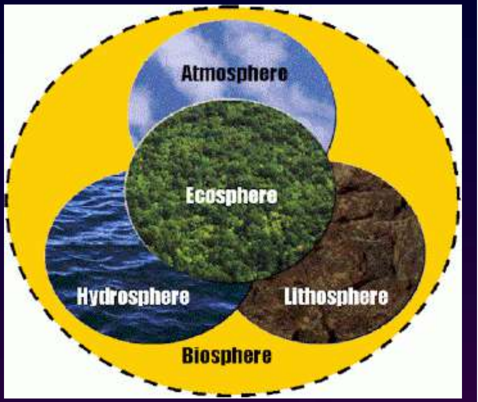

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- Total carbon sink ~5 Gt/year due to Photosynthesis and Soils (30%), Oceans (25%), and Sediments/rocks (<1%), meaning 9-5=4 Gt/year left to the atmosphere $\longrightarrow$ increase in CO_2 (greenhouse gas). Ratio of CO_2 to carbon is 3.66, so emission of 1K tonnes of CO_2 is equivalent to adding 366 tonnes of Carbon to the atmosphere !!!!

NCER

- Why non-conventional energy resources (NCER) ?

Energy Usage

- Clean ← Air → Pollution-free
- Drinking ← Water → Purification
- Abundant ← Food → Agriculture
- Eco-friendly ← Shelter → Construction materials
- Sustainable ← Clothing → Fiber Production

[Natural (biomass),Synthetic]

Bioenergy

NH_3

- Ammonia production (Haber’s process) : $3H_2 + N_2 \rightarrow 2NH_3$.

  This reaction require significant amount of Hydrogen, which is provided by natural gas by *steam reforming* process. In agriculture, the largest consumer of fossil fuel is ammonia production. Specific fossil fuel input to fertilizer production is primarily the natural gas. After hydrogen is obtained, after compression of H and N, in ammonia synthesis vessel it is heated at 500°C in presence of catalyst Fe, Al_2O_3 etc.
- So, one has to think about secondary process to generate Ammonia without the consumption of regular fossil fuels!!

Bioenergy

- Bioenergy ➔ Bio + energy. Bio is renewable biological material, e.g. plant, grass, bacterial & algal population because of perennial source of Solar energy. Bio can be classified as *renewable materials originating from different life forms*, called Biomass. As energy contained in Biomass is used for energy production, so how biomass is formed on Earth? The renewable materials include, Straws, Wood, Animal Waste, Microbial Waste, Algael Biomass etc.

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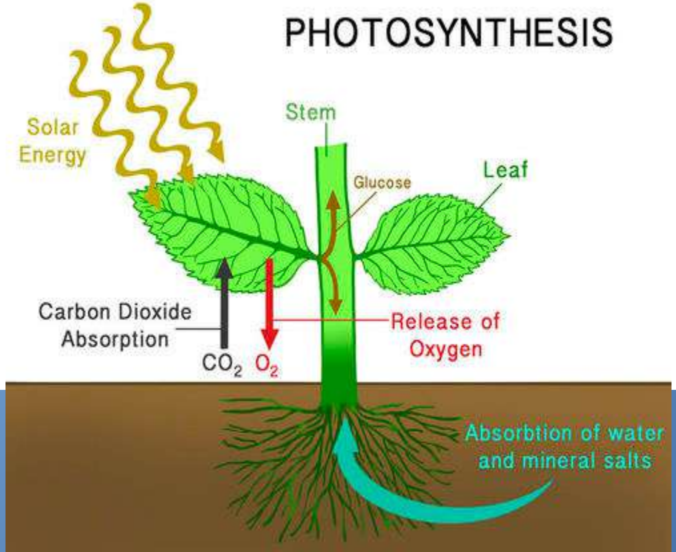

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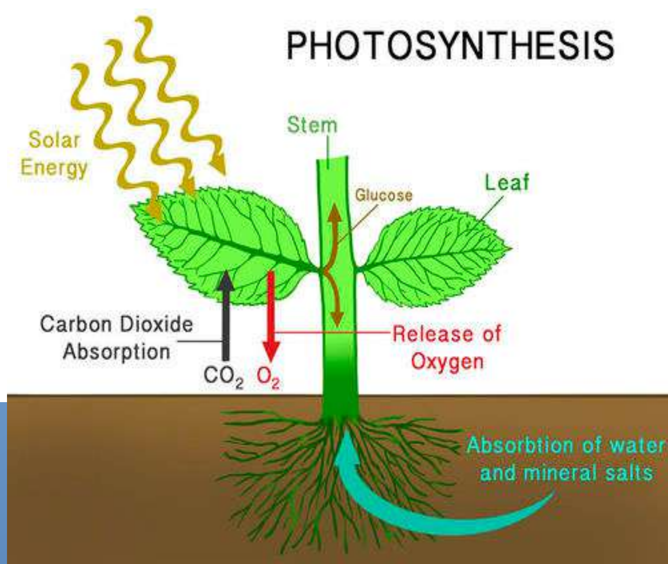
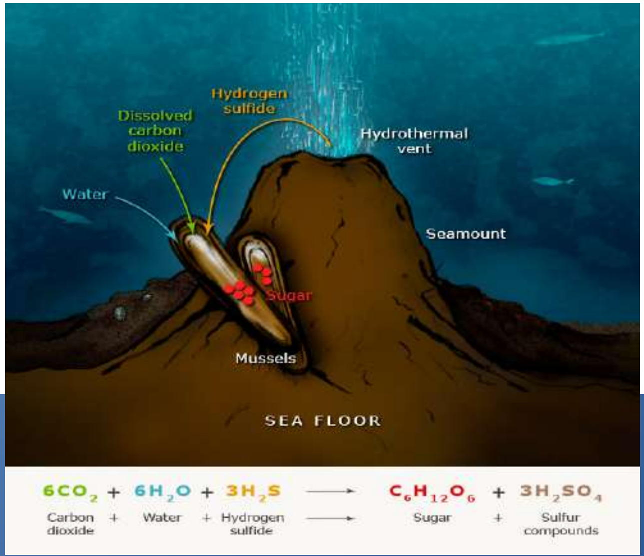
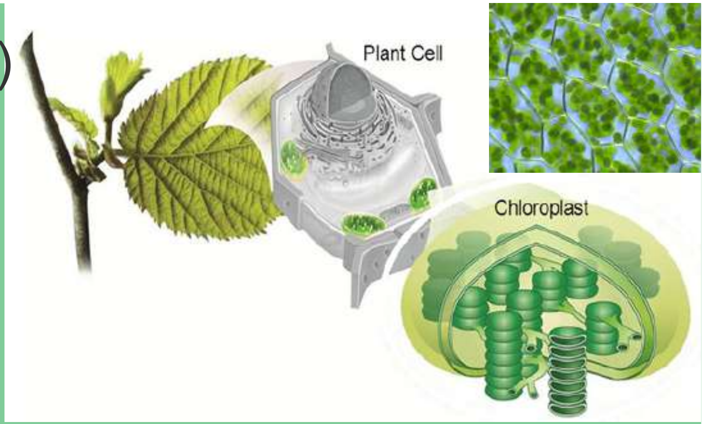
- How biomass is formed on Earth??: (a) Photosynthesis ➡ Photo (light dependent) + synthesis. Anything that grows on surface of Earth or waterbodies by the light from Sun is photo-synthetically driven. (b) Chemosynthesis ➡ Discovery of hydrothermal vents in late ‘70s & early ‘80s in deep under the sea where light can’t penetrate, but life exists by depending on transition metal sulfides, hydrogen sulfides etc. Possible in Mars habitability search, where a human colony can set up.







In <u>photosynthesis</u>, solar energy (photons or light quanta) is trapped by solar harvester by leafs or green pigment that constitutes of Chlorophyll. Across the membrane of Chloroplast, a chemical process (a charge gradient) is driven like in a battery chemical synthesis. Energy rich molecules are obtained that are termed as Biomass → (natural) biological solar panels (different plants, bacteria, algae). ***Efficiency of photosynthesis is directly correlated with biomass formation.*** In desserts at water scarce area, some bushes stay due to this.

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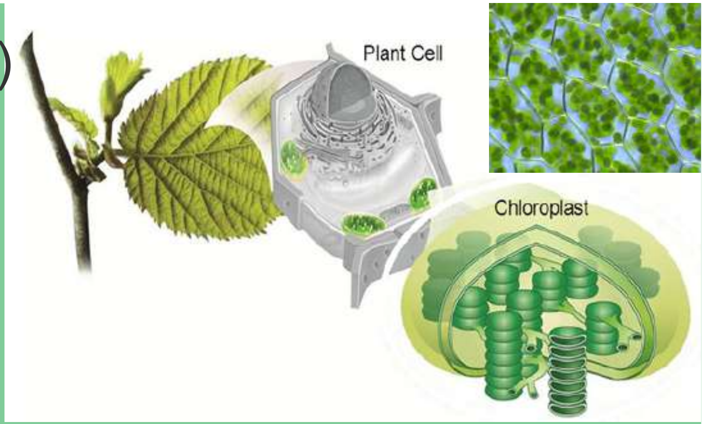

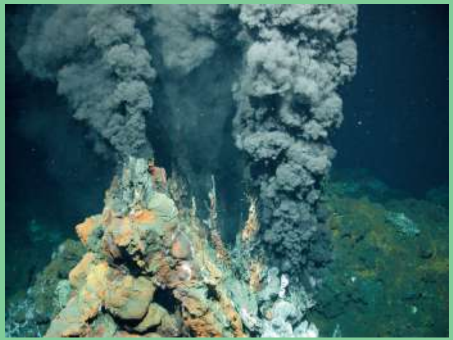

In **chemosynthesis** deep down under the ocean floor, magma & sulfide rich gases come out from "brown & white smokers" revolving that hydrothermal vents exists, without O_2, without light, at high pressure.

Spectrum of Bioenergy

- Roadmap of Bioenergy → Conversion of Biomass into usable fuel, with insights from formation of fossil fuels, now in an industrial setup, after conducting pilot studies in laboratory trials and pilot plants, finally to industry which led to ***bio-refinery*** and byways fuel production → Bio-diesel, Bio-ethanol, highly inflammable biomaterial to be used for transportation sector as well as for domestic use (cooking).

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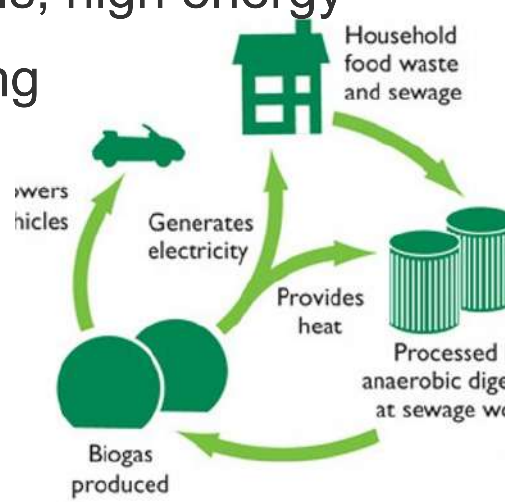
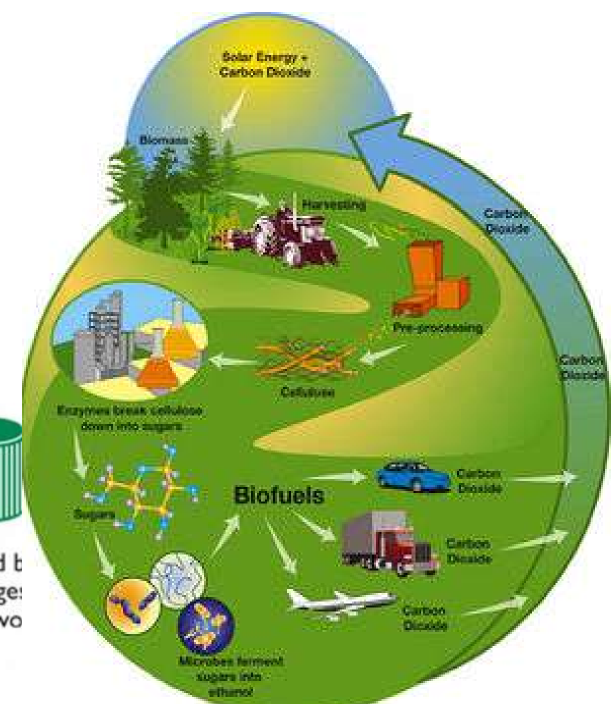
- Nature of Biomass resources in different forms ➲

(a) ***Biofuels*** (solid, liquid, gas), **(b)** ***Biopower*** (innovative energy efficient technologies for converting biomass into graphene-like materials, battery-materials, high energy value materials). This has to go according to consumer market acceptibility, sustainibility, new World order of energy economy.





Biomass

Average estimate of global biomass (1990–2008) is ~ 600GtC. Density of standing phytomass ~ 5 t/ha (tonne/hectare) for tundra, 1K t/ha for tropical rain forests, which have 3/5th of phytomass. Density of bacteria in soil ~ 10–1K gm/m^2 & for soil fauna, ~ 5–15 gm/m^2. Vertebrate biomass is dominated by domestic animals (cattle, buffalo, pigs) with a weight of ~ 600 megatons(Mt) or 125 MtC.

- Tundra = type of biome where tree growth is hindered by low temperatures and short growing seasons,
- Phytomass = total amount of living organic plant matter.

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Biomass

Gross primary productivity (GPP) is the total amount of new phytomass that is photosynthesized during a time period, and the global GPP is ~ 120 Gt/yr of carbon (Gt/yrC). Autotrophic respiration (R_A) is reoxidation, which limits the amount of sunlight converted to plant tissue. Net primary production (NPP) is equal to GPP-R_A. Spatial variability of NPP range from 1K $gm/(m^2/yr)C$ in equatorial zones, 400–600 $gm/(m^2/yr)C$ in temperature mid-latitudes & < 300 $gm/(m^2/yr)C$ in the interior of Asia, Australia along with Siberia & western North America.

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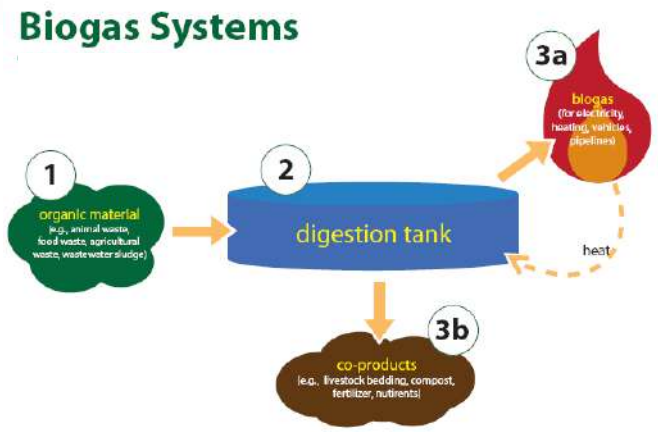
- *WOOD* ➔ major source of energy for 2.6 billion people (fuel wood, charcoal, dung for cooking/heating). In Africa & Asia, fuel wood and charcoal provide 50-90% of the energy.

Biomass

Collection of fuel wood is primarily the work of women and children. In the Sahel region (Africa), women walk on ~ 20 km/day to collect wood, & in towns, families spend 1/3rd of income on wood/charcoal. It takes 10kg of wood to make 1kg of charcoal. Dung from cows, buffalos, yaks, and camels, is the other major source of energy for heating/cooking in rural areas. Fresh manure is mixed with straw & water, flattened into patties, and dried. Open fires in confined spaces is a major health risk & efficient but costly stoves are problem for the poor people.

Anaerobic Digestion



- Anaerobic digestion is a series of biological processes in which microorganisms break down biodegradable material in the absence of O_2. End products is biogas, which is combusted to generate electricity and heat, or can be processed into renewable natural gas and transportation fuels.

AKB

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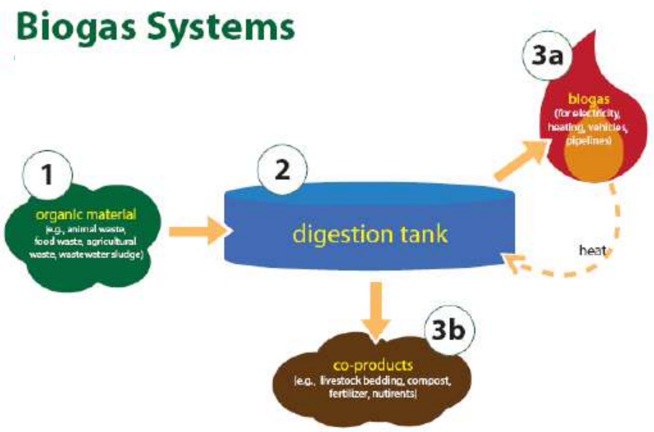

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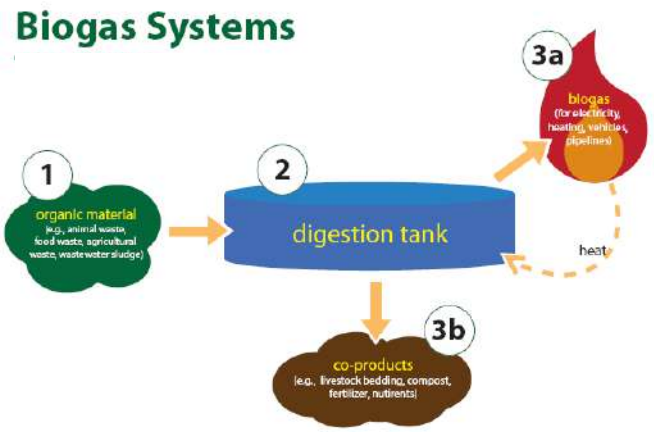

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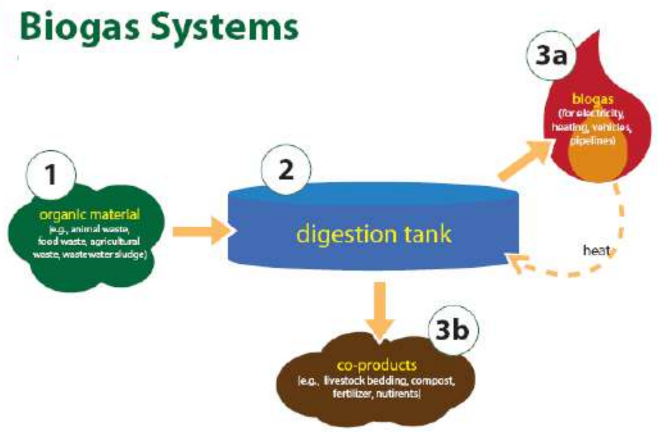
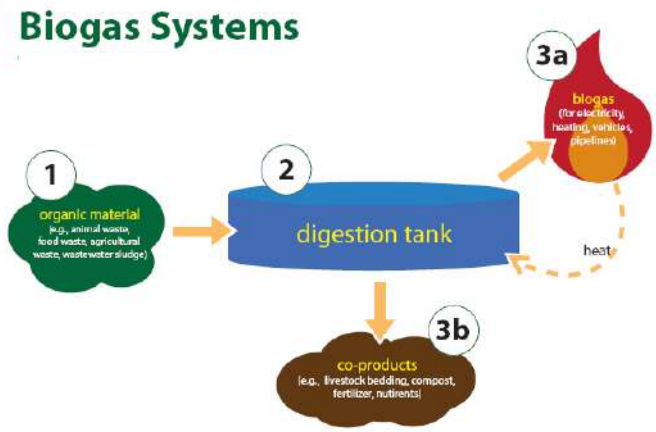
- **Biological Process** ➡ Digestion process begins in 4 stages with (i) bacterial hydrolysis of the input materials in order to break down insoluble organic polymers such as carbohydrates and make them available for other bacteria. ...

Anaerobic Digestion



(ii) *Acidogenic* bacteria then convert the sugars and amino acids into CO_2, H_2, NH_3 & organic acids. (iii) *Acetogenic* bacteria then convert these resulting organic acids into acetic acid, along with additional CO_2, H_2. (iv) Finally, methanogenesis convert acetates into NH_3 & CO_2 while H_2 is consumed.

Anaerobic Digestion



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- **Digester Technologies** ➡ Different anaerobic digester systems are commercially available, based on organic waste stream type (manure, municipal wastewater treatment, industrial wastewater treatment and municipal solid waste):
  Manure: Anaerobic digestion systems for livestock manure operate to reduce methane emissions, odors, pathogens & weed seeds, and produce biogas. They fall into 4 general categories: (i) Covered anaerobic lagoon digester, (ii) Plug flow digester, (iii) Complete mix digester, (iv) Dry Digestion.

Anaerobic Digestion

- **Municipal Wastewater**➔ Wastewater treatment plants employ anaerobic digesters to break down sewage sludge and eliminate pathogens in wastewater. Technologies available for municipal wastewater fall into three general categories - (i) mesophilic, (ii) thermophilic & (iii) temperature-phased systems.

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- **Municipal Solid Waste (MSW)** ➔ Anaerobic digestion of the organic fraction of MSW provides a controlled process of capturing methane, compared to waste. Digestion of mixed solid waste is done as part of compliance with directives to stabilize the organic fraction of the waste stream prior to disposal. Current trend is toward anaerobic digestion of source separated organic waste streams, including food waste, yard trimmings and soiled paper.

Nuclear and Bioenergy

We posed purpose of nuclear energy and Bioenergy as a futuristic renewable contribution as alternative to energy production, energy consumption and energy utilization. Biofuels, Biopower & Bioenergy distribution may lead to sustainable future.