ENVC 24 : Energy and Environment

Part-2 : Nuclear Energy & Bioenergy

Vermont, USA

Cattenom, France

Trombay, India

AKB

Conventional energy sources

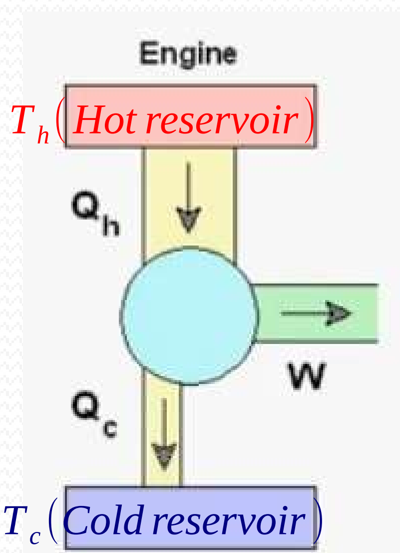
- In Thermal power plant, work is available from mechanical energy released by fuel burning in a Thermodynamic cycle, which using electrical generator is converted. Depending on nature of working fluid, thermal power point are classified as ➔ (a) Gas power cycle (GPC), (b) Vapour power cycle (VPC).
-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

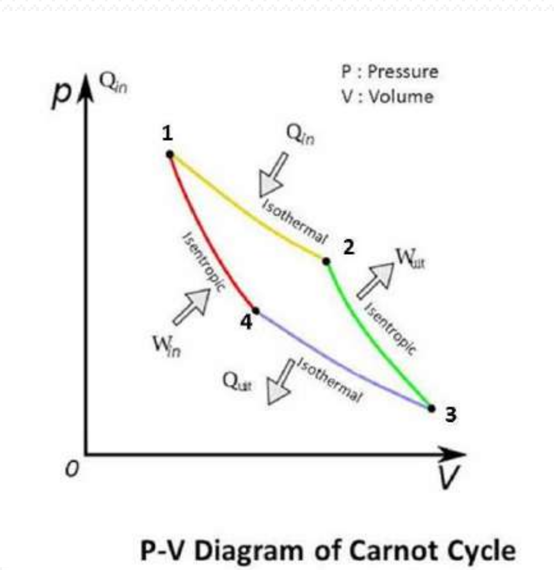
Thermodynamics of Engines

- Heat engines convert energy into work.

$$\text{Efficiency}\ \eta = \frac{\text{Work Done}}{\text{Heat Absorbed}} = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = \frac{T_h - T_c}{T_h}(\text{Carnot}).$$

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





indicator diagram

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Thermodynamics of Engines

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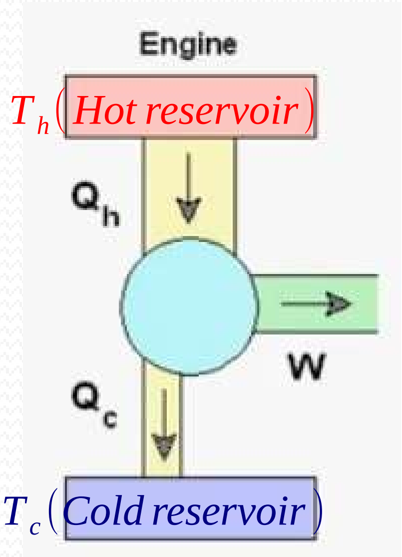
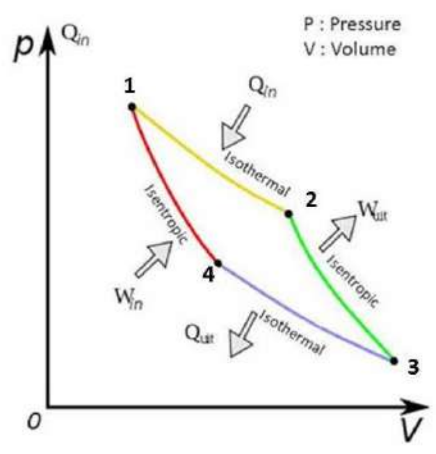
Carnot cycle : 1 → 2 reversible isothermal process : $PV = RT =$ constant.

2 → 3 reversible adiabatic process : $PV^{\gamma} =$ constant.

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

4 → 1 reversible adibatic process : $PV^{\gamma} =$ constant.





P-V Diagram of Carnot Cycle

indicator diagram

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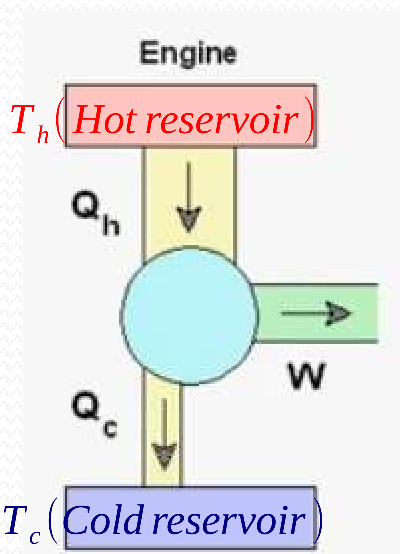
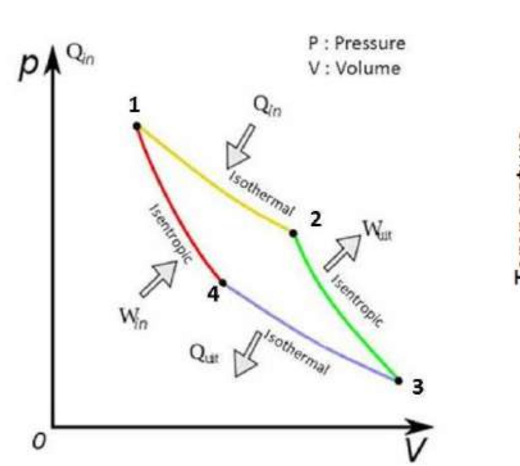
Thermodynamics of Engines

- Heat engines ➲ convert energy into work.

$$\text{Efficiency } \eta = \frac{\textbf{Work Done}}{\textbf{Heat Absorbed}} = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = \frac{T_h - T_c}{T_h} (\text{Carnot}).$$

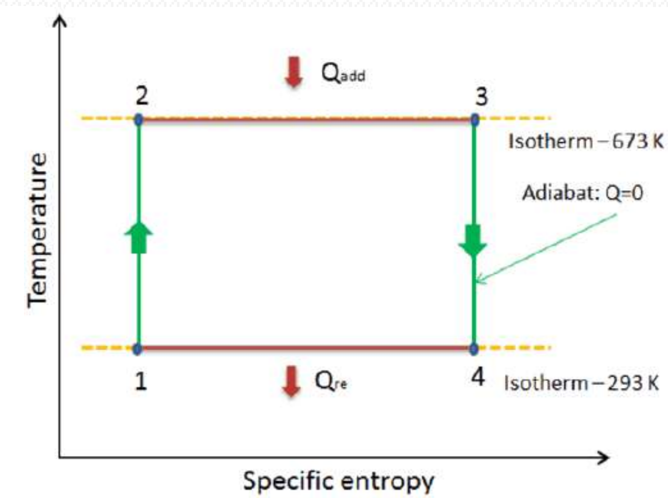
- Entropy $dS = \frac{dQ}{T}$ (as Q/T = constant, resulting to T.D. scale of temperature).





P-V Diagram of Carnot Cycle

indicator diagram



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

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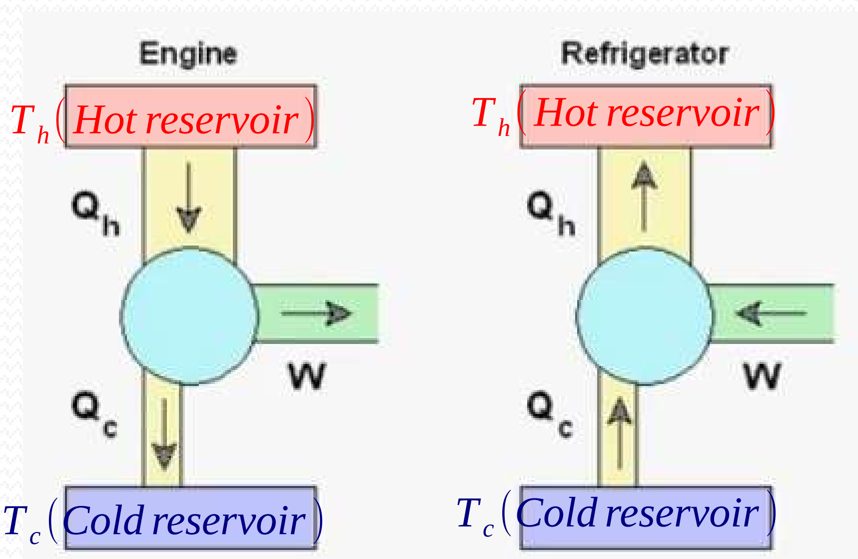
Thermodynamics of Engines

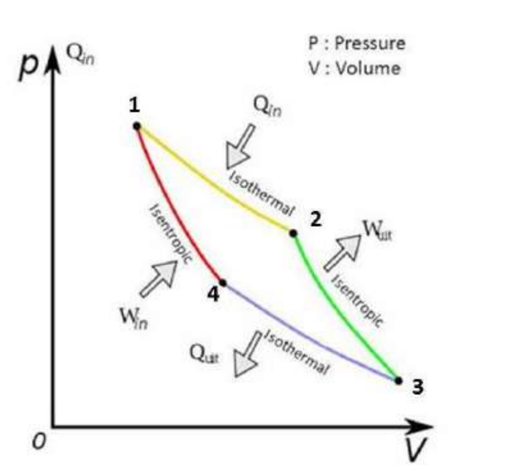
- Heat engines ➲ convert energy into work, *i.e.* opposite of refrigerator/heat-pump.

$$\text{Efficiency}\ \eta = \frac{\text{Work Done}}{\text{Heat Absorbed}} = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = \frac{T_h - T_c}{T_h}\ (\text{Carnot}).$$

$$\text{Coefficient of Performance}\ (COP) = \frac{\text{Heat Absorbed}}{\text{Work Done}} = \frac{Q_h}{W} = \frac{Q_h}{Q_h - Q_c} = \frac{T_h}{T_h - T_c}\ (\text{Carnot}).$$

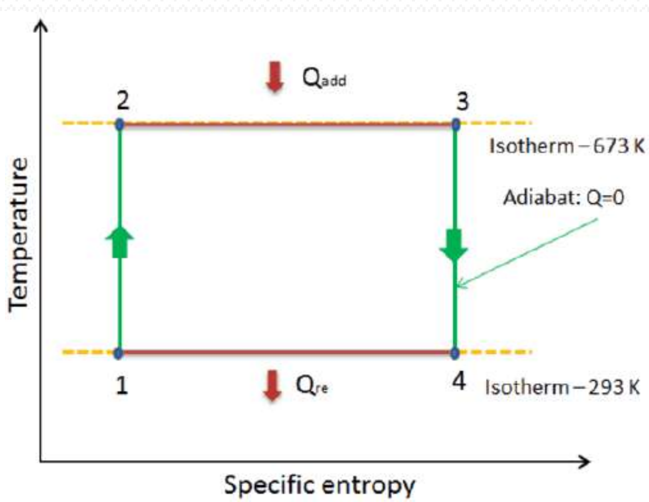
- Carnot's efficiency is ***independent*** of fuel/working substance and depends on hot and cold reservoir temperature only!





P-V Diagram of Carnot Cycle

indicator diagram



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

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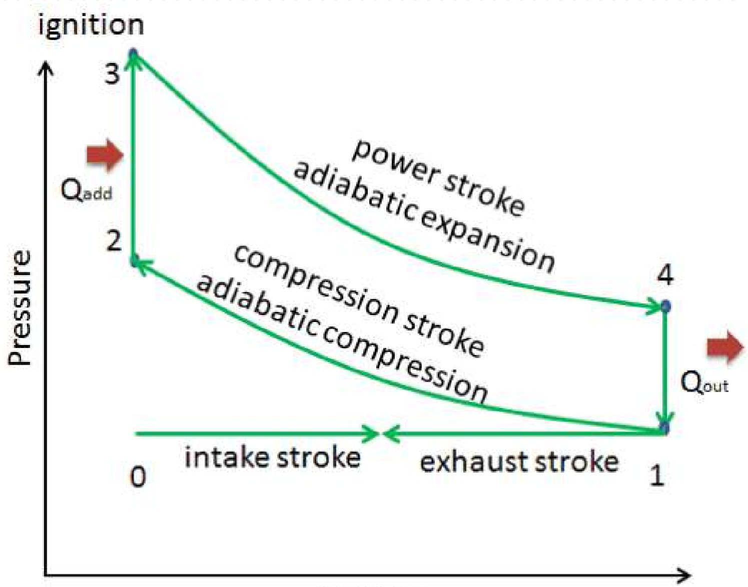
Otto, Diesel & Rankine cycle

- 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.

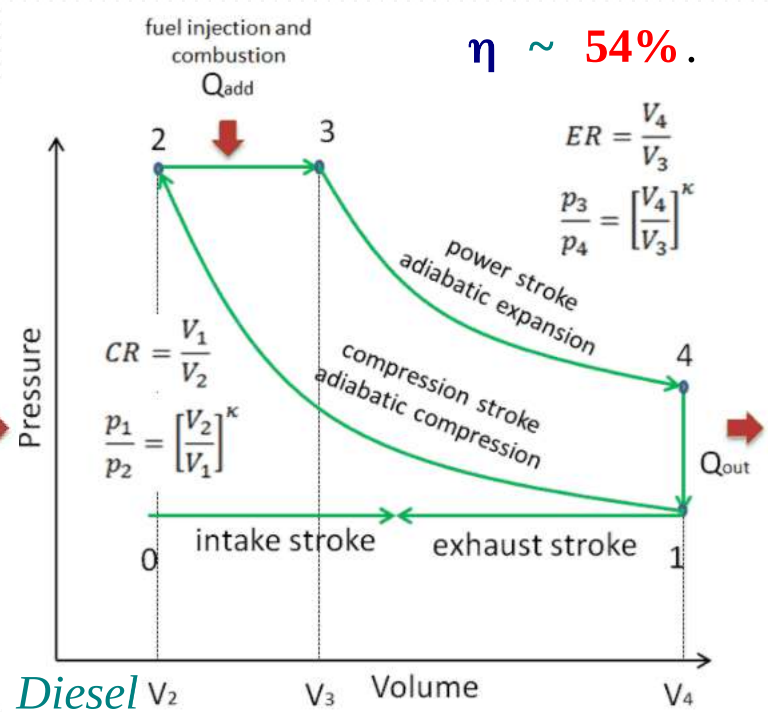
1 ➔ 2 : low to high pressure (liquid)
2 ➔ 3 : constant P heating (liquid ➔ vapour)
3 ➔ 4 : vapour expansion (P & T decrease)
4 ➔ 1 : condensation @ constant P (liquid)

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



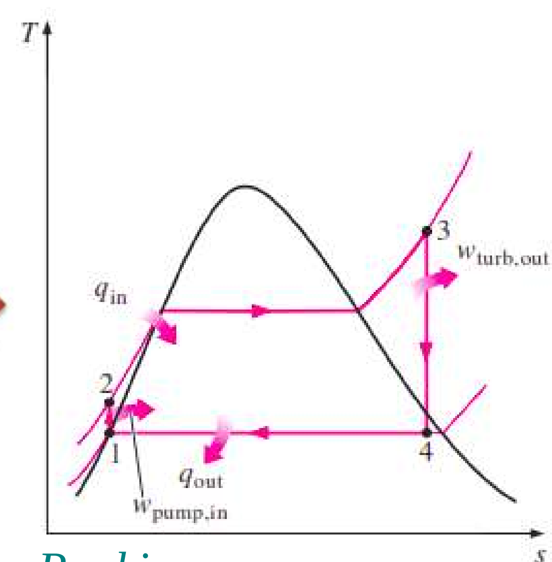
Otto

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



Diesel

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



Rankine

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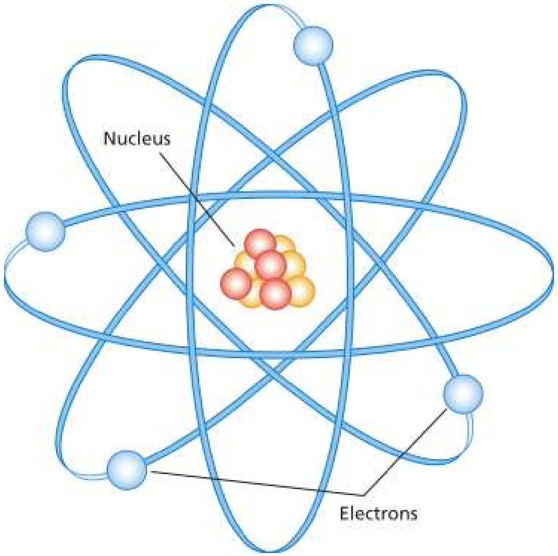
Efficiency Improvement

- 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

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

Bohr Model



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

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

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

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

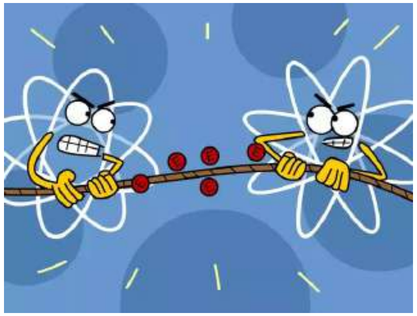
$$m_e = 9.1\, x\, 10^{-31}\, kg$$

Atoms & Chemical Bond

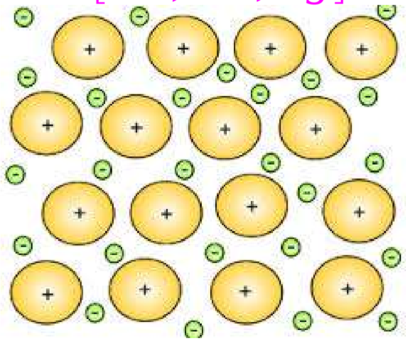
- Chemical bonds form by bringing atoms from infinity to closest separation, so that total energy is negative (cohesive energy) = attractive force of negatively charged cloud of one atom with positive nuclear charge of other atom + repulsive force of overlapping negatively charged electron clouds & positively charged nucleus of two atoms.
- Types of bond : (a) Ionic Bond, (b) Covalent Bond, (c) Metallic Bond, (d) Hydrogen bond, (e) van der Waal's Bond.

$[NaCl, KCl]$

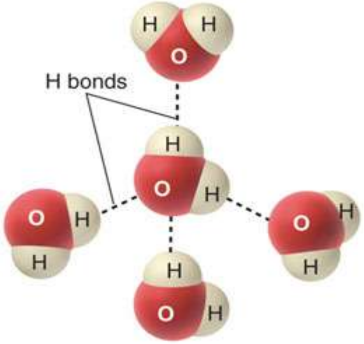
$[F_2, CO_2, HCl]$



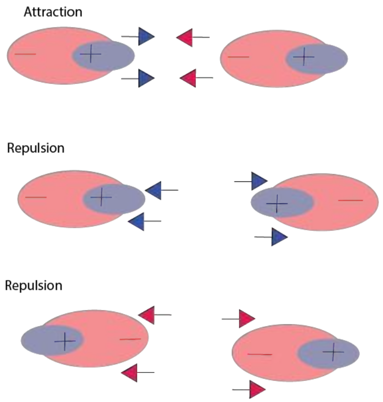
$[Cu, Au, Ag]$



$[H_2O]$



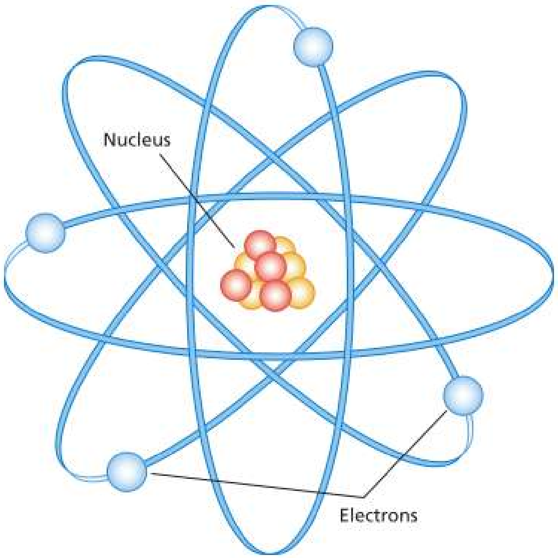
[most fluids]



What is Nuclear Energy?

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

Bohr Model



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

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

- 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?

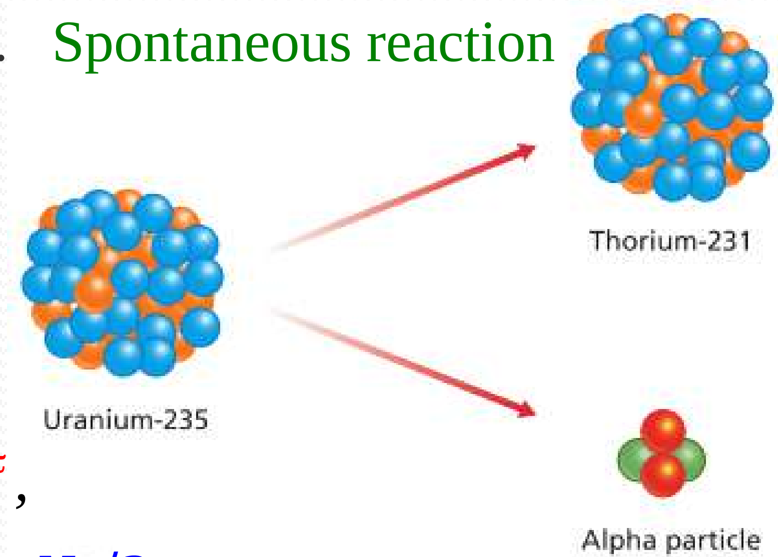
- Number of protons + neutrons = mass number (superscript). X_A^M
- Radioactive materials, rather than coal, as sources of thermal energy by radioactive spontaneous disintegration of atomic nucleus.

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

⇒ Total protons + neutrons (mass no) = constant. Spontaneous reaction

⇒ Total electric charge = constant.

⇒ Total energy of atoms = constant.



- Half life $t_{1/2}$ of radioactive isotopes is the time required when half of the sample remains.

From $\frac{dN}{dt} = -\lambda N$, we find $N(t) = N_0 e^{-\lambda t} = N_0 e^{-t/\tau}$,

where $\tau = 1/\lambda$ is the mean lifetime. At $t_{1/2}, N(t) = N_0/2$,

so, $N(0)/2 = N_0 e^{-t_{1/2}/\tau}$ ⇒ $t_{1/2} = \tau \ln 2$.

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

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What is Nuclear Energy?

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

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.

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 $N(t) = N_0 e^{-\lambda t}$, $R = \lambda N = \lambda N_0 e^{-\lambda t}$.

- S.I. unit of radioactivity is Bacquerel (Bq).

  1 Bq = 1 disintegration/second. MBq and GBq are also used to designate 6^{th} and 9^{th} power of 10.

- Common unit of measuring activity is Curie (Ci). It is defined as $3.7 x 10^{10}$ disintegrations/second. 1 Ci = 37 GBq. Another used unit is Rutherford (rd) which is 10^6 disintegrations/second. 1 micro Rutherford = 1 Bq.

Numericals

(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?

- (a) Decay constant $\lambda = 4.28\,x\,10^{-4}/\,year$. So, mean life $\tau = \frac{1}{\lambda} = 2336\,years$.

  Half life $t_{1/2} = \tau \ln 2 = \frac{0.6931}{\lambda} = 1619\,years$.

  (b) $t_{1/2} = 5\,hrs$. So, decay constant $\lambda = 0.6931/5 = 0.1386\,per\,hour$.

  We know, $N(t) = N_0 e^{-\lambda t}$, and in this case $\frac{N(t)}{N_0} = \frac{1}{3}$, $so\ \ 3 = e^{\lambda t}$

  or $\ln 3 = \lambda t$, or $t = \frac{2.3026\log_{10} 3}{0.1386} = 7.93\,hrs$.

  (c) Mean life $\tau = \frac{1}{\lambda} = t$ in this case. So from, $N(t) = N_0 e^{-\lambda t}$, we obtain, $\frac{N(t)}{N_0} = e^{-\lambda\,x\,\frac{1}{\lambda}} = e^{-1}$.

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

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

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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.

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

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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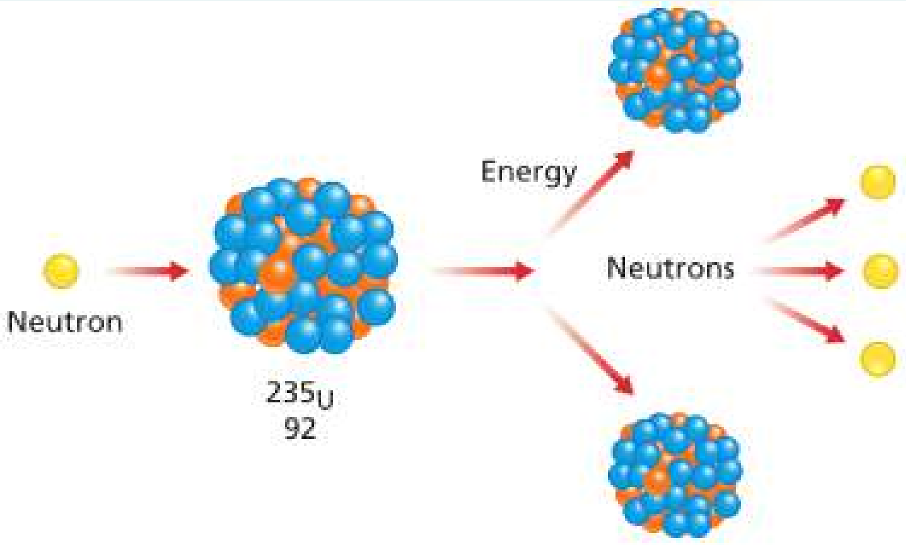
Atomic Fission

- **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.

$$n + U_{92}^{235} \Rightarrow U^{*}{}_{92}^{235} \Rightarrow Ba_{56}^{144} + Kr_{36}^{89} + 3n.$$



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.

- **Gamma/beta Ray** ⇨ $n + U_{92}^{238} \rightarrow U^{*}{}_{92}^{239} + \gamma \Rightarrow U^{*}{}_{92}^{239} \rightarrow Np^{*}{}_{93}^{239} + \beta,$

$$\Downarrow$$

$$Np^{*}{}_{93}^{239} \rightarrow Pu^{*}{}_{94}^{239} + \beta.$$

$t_{1/2}(Uranium) = 23$ minutes
$t_{1/2}(Neptunium) = 56$ hours
$t_{1/2}(Plutonium) = 24{,}000$ years

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

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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 $\Rightarrow$ 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

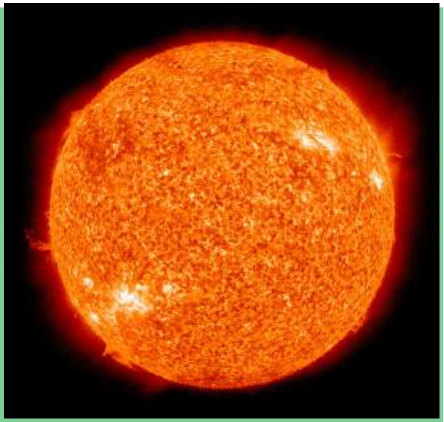
Mass Number	Series	Parent	Half-life in years	Stable end-product
4n	Thorium	Th_{90}^{232}	1.39×10^{10}	Pb_{82}^{208}
4n + 1	Neptunium	Np_{93}^{237}	2.25×10^{6}	Bi_{82}^{209}
4n + 2	Uranium	U_{92}^{238}	4.51×10^{9}	Pb_{82}^{206}
4n + 3	Actinium	U_{92}^{235}	7.07×10^{8}	Pb_{82}^{207}

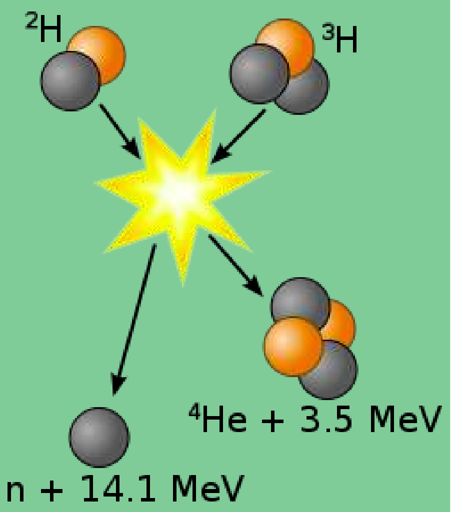
- End product of Uranium Series A=(4n+2) : Pb^{206} or Pb^{207} or Pb^{208} ??

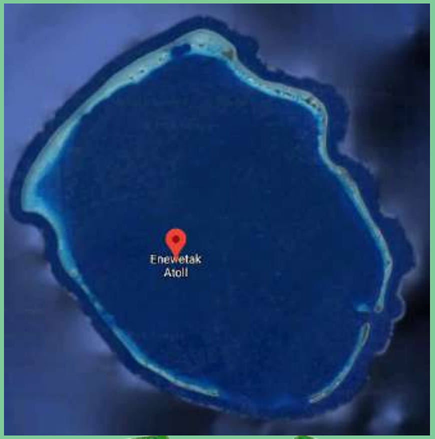
  While $4n+2 \neq 207, 4n+2 \neq 208$ for any integer n, only for n=51, $4n+2=206$.

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

- 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.
- Fusion of deuterium with tritium create Helium-4 & neutron with a release of 17.59MeV of Kinetic Energy. These fuels stars.
- Thermonuclear fusion test ➡ Ivy mike Hydrogen Bomb (1952).







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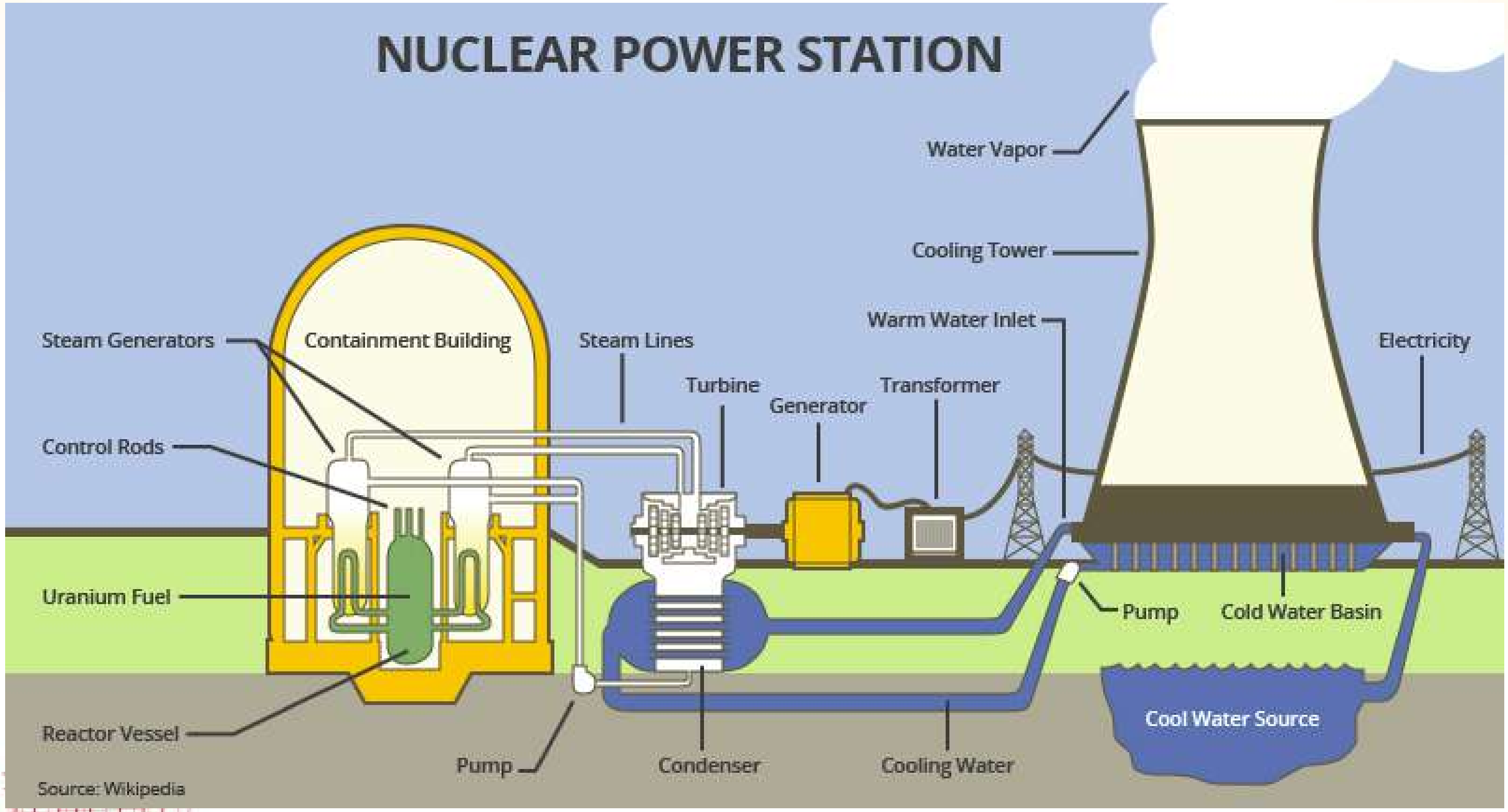

- **Control rods** control the fission rate of Uranium/Plutonium. They are composed of **Boron**/**Silver**/**Indium**/**Cadmium** capable of absorbing many neutrons without themselves fissioning. Because these elements have different capture crosssection for neutrons of varying energies, composition 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.

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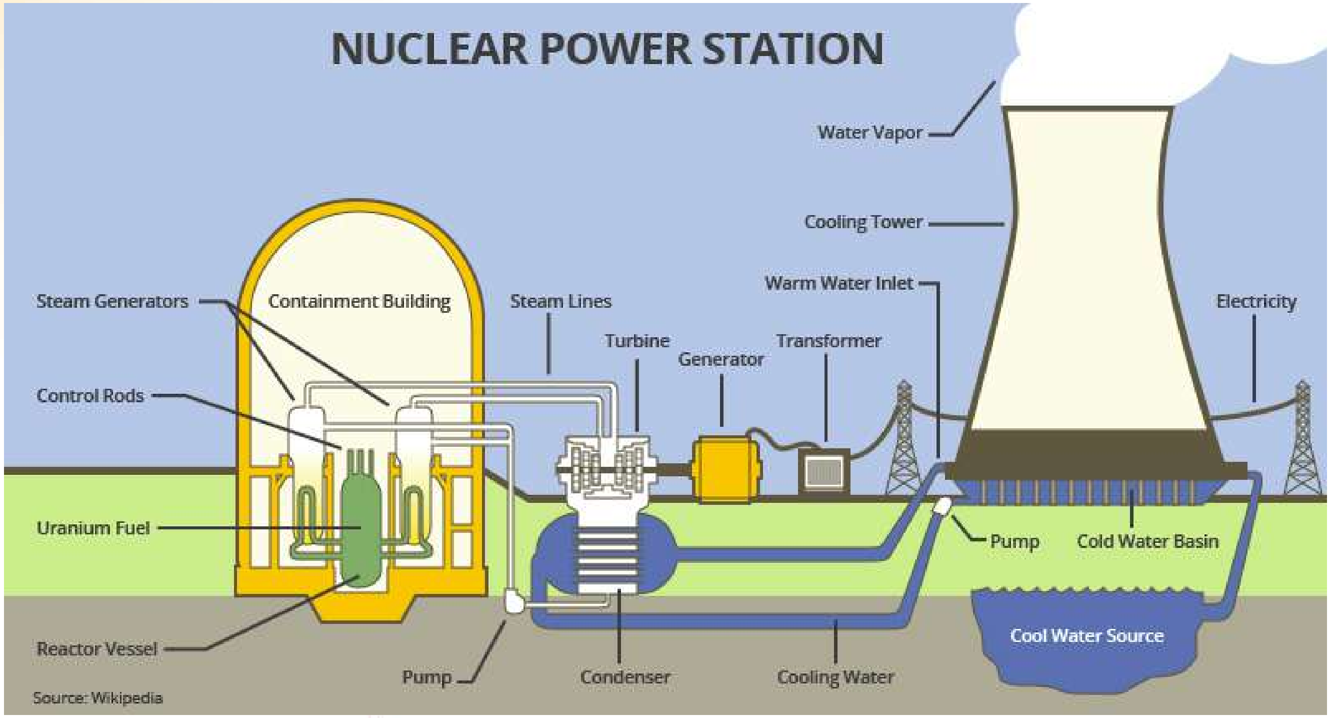
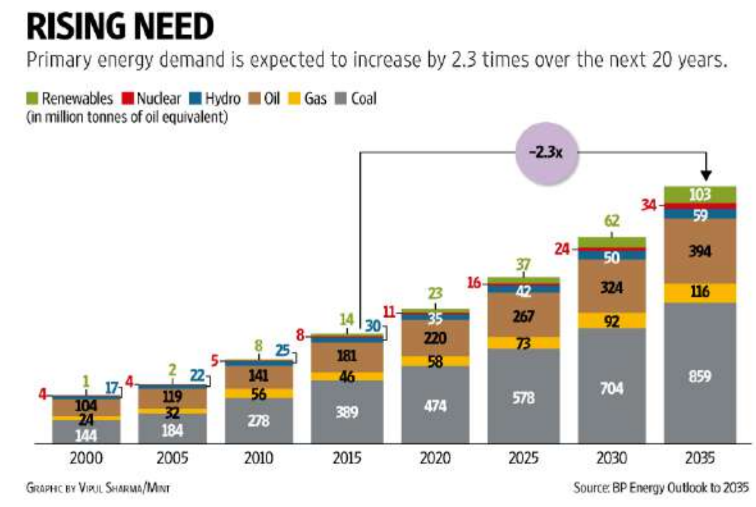
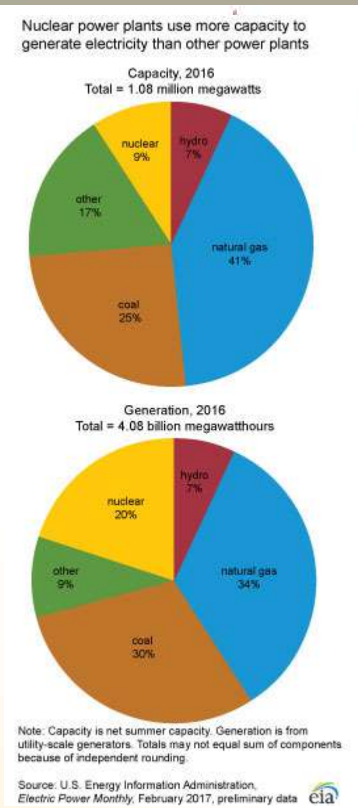
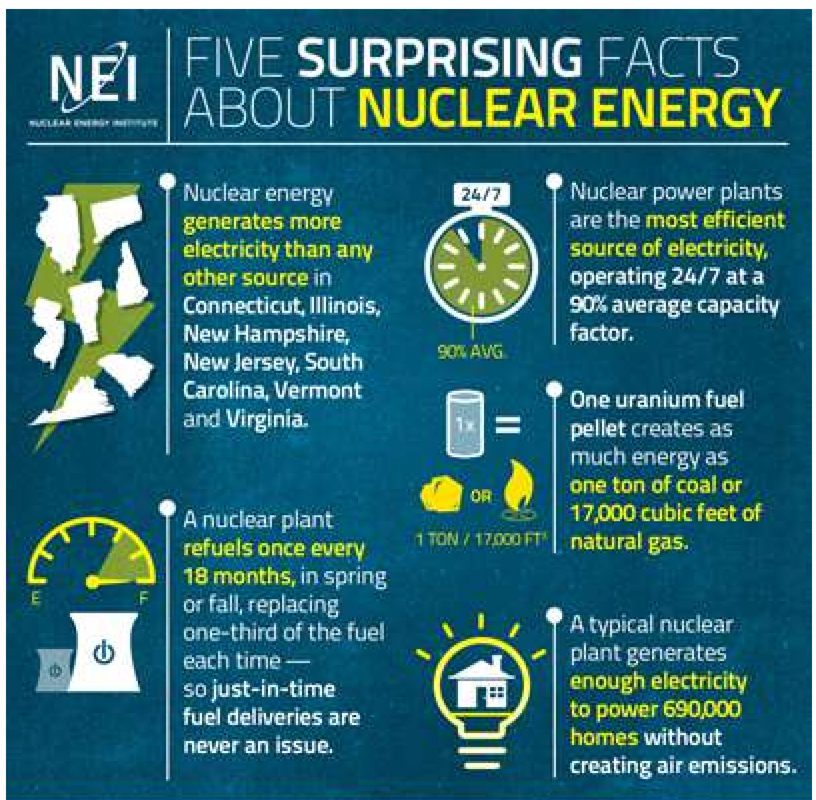
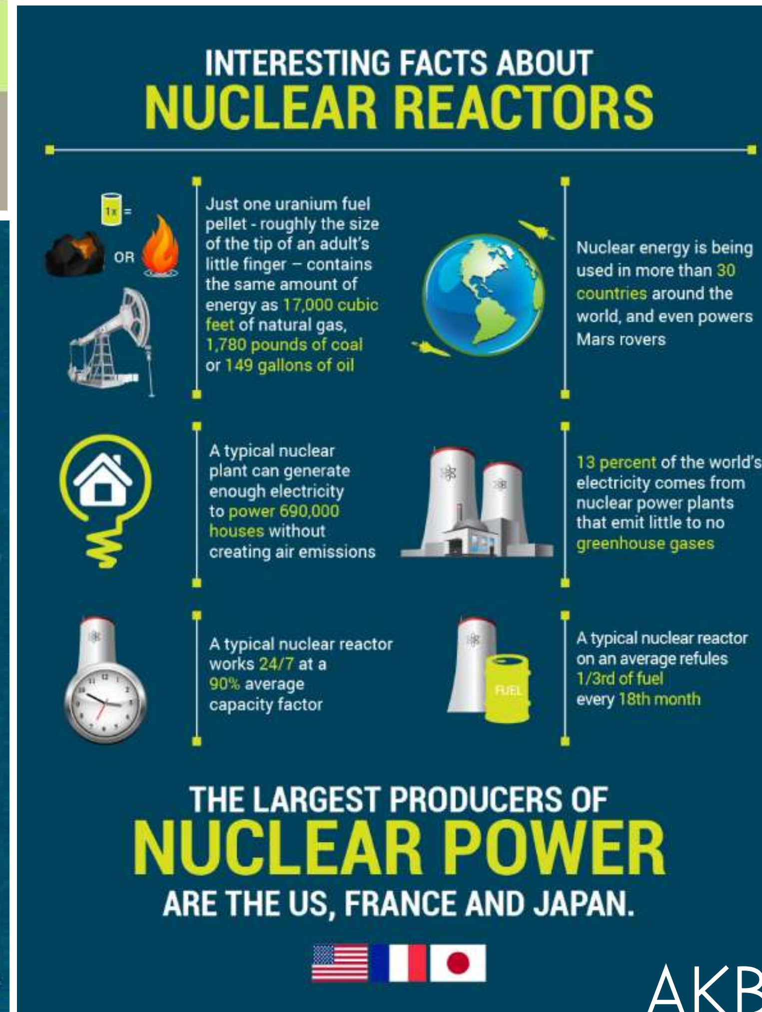

NUCLEAR POWER STATION
Water Vapor
Cooling Tower
Warm Water Inlet
Steam Generators
Containment Building
Steam Lines
Electricity
Turbine
Transformer
Generator
Control Rods
Uranium Fuel
Pump
Cold Water Basin
Cool Water Source
Reactor Vessel
Pump
Condenser
Cooling Water
Source: Wikipedia


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)
~2.3x
2000 2005 2010 2015 2020 2025 2030 2035
Graphic by Vipul Sharma/Mint
Source: BP Energy Outlook to 2035

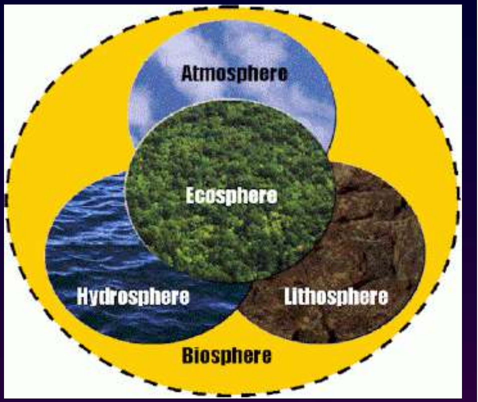

Nuclear power plants use more capacity to generate electricity than other power plants
Capacity, 2016
Total = 1.08 million megawatts
nuclear 9%
hydro 7%
other 17%
natural gas 41%
coal 25%
Generation, 2016
Total = 4.08 billion megawatthours
hydro 7%
nuclear 20%
other 9%
natural gas 34%
coal 30%
Note: Capacity is net summer capacity. Generation is from utility-scale generators. Totals may not equal sum of components because of independent rounding.
Source: U.S. Energy Information Administration, Electric Power Monthly, February 2017, preliminary data
eia


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.

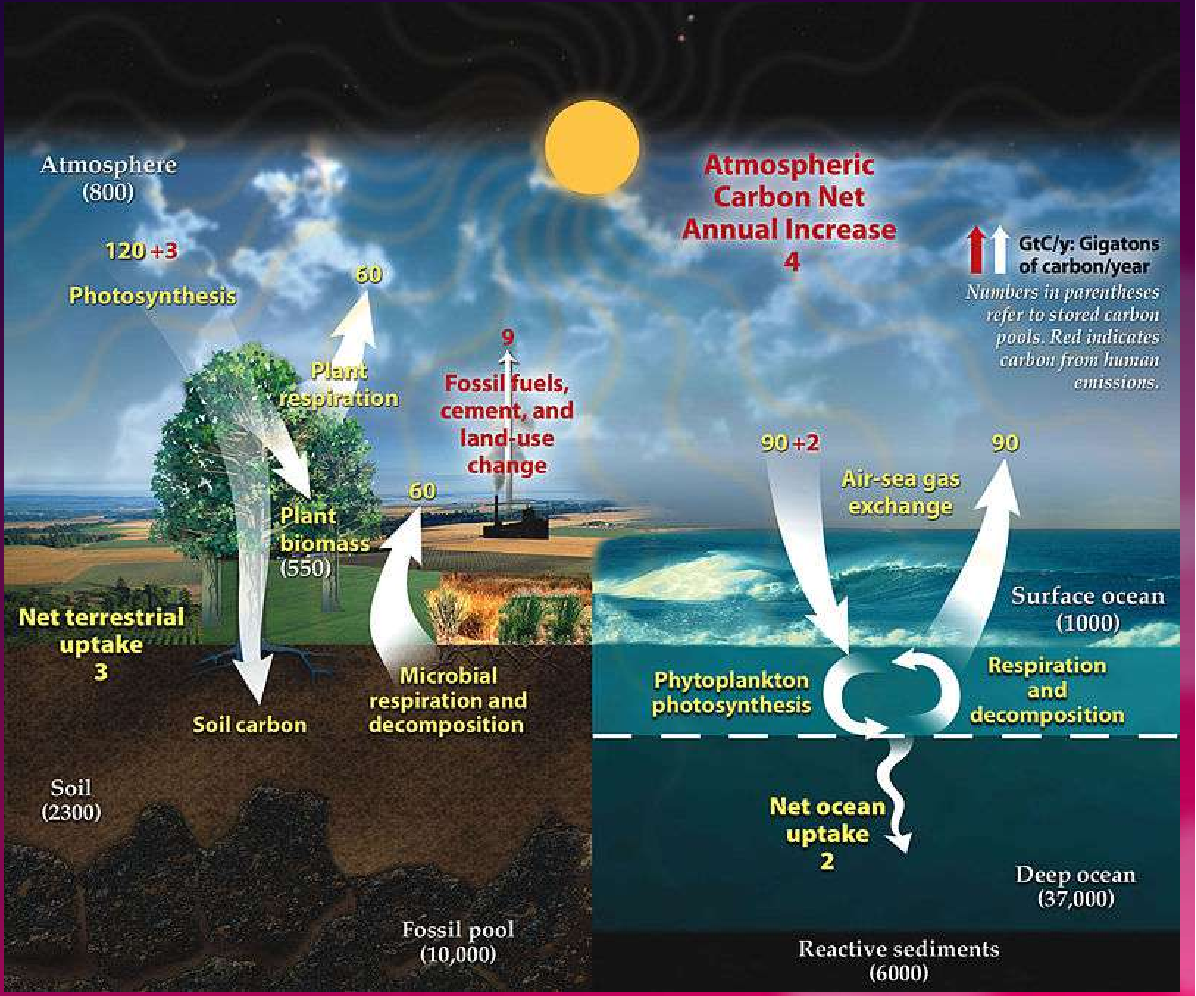
AKB

Carbon Cycle



- Biochemical exchange between reservoirs: atmosphere, biosphere, soil (pedosphere), ocean, burial in sediments (source of fossil fuels), earth crust (lithosphere, limestone/rocks).
- Carbon content: Ocean: 38K Gt, Fossil fuels:1.5K Gt, Atmosphere: 730 Gt, Limestone: 100Pt.
- Exchange rate Atmosphere-Ocean: 2Gt/year, burial rate sediments: 0.2Gt/year, transport into Ocean: 1.4Gt/year, Human activity = combustion of fossil fuels (7Gt/year)+deforestration (2Gt/year) = 9Gt/year.

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



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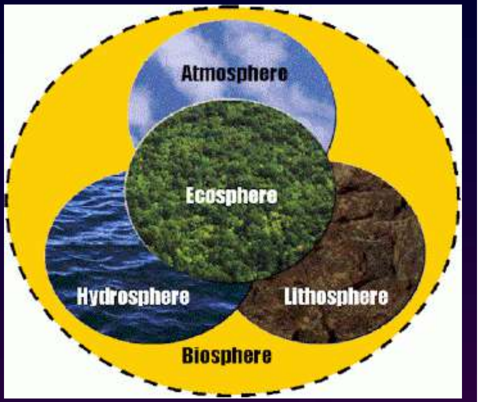

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- Total carbon sink ~5 Gt/year due to Photosynthesis and Soils (30%), Oceans (25%), and Sediments/rocks (<1%), meaning 9-5=4 Gt/year left to the atmosphere $\longrightarrow$ increase in CO_2 (greenhouse gas). Ratio of CO_2 to carbon is 3.66, so emission 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. There are 2 ways to harness energy, **(a)** Burning of Solid Biomass (Heat/Power output). Wood is traditionally used for fuel & alcohol. Cowdung cakes is another example. **(b)** Generate liquid Biofuels e.g. Biodiesel, Bioethanol (more energy efficient). While (a) is a traditional route since the discovery of fire, (b) is the new-age route that demands discovery and optimization – how to convert these naturally available Biomass naturally into highly combustible, high utility and cleaner form of energy.

Biomass Formation

- If we can understand how fossil fuels were made below the earth crust by pressure / temperature without oxygen for several million years, then can we optimize the time-scale to few days artificially??
- 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.