

## 01. Energy

### By constant force

work done by a force == force \* displacement

$$W = FS$$

### Law of conservation of energy

Energy can neither be created nor destroyed, it can only be transformed from one form to another

### Kinetic energy

$$\text{linear motion} - K = \frac{1}{2}mv^2$$

$$\text{angular motion} - \frac{1}{2}I\omega^2$$

- I = Moment of inertia of object (dependent on mass distribution of object)

- $\omega$  = angular velocity of the rotating object

– Rad/second

–  $v = \omega * \text{radius}$

### Gravitational potential energy

$$U = mgh$$

### Power

Rate of doing work or rate of consumption of energy

$$P = \frac{\Delta W}{\Delta t}$$

Work done, W, by a system in time t

### Requirements of an energy system

#### Energy resource

- Clean energy
  - Wind Energy
  - **Hydro energy** - Come from river and dams
  - Ocean energy Only refers to energy coming from ocean currents etc
  - Solar energy
  - Biomass
  - Non-Renewables:
    - Geothermal
    - Nuclear
- Fossil fuels
  - Coal
    - \* Greater carbon content and more impurities - More carbon dioxide and greater air pollution
    - \* Solid so difficulty in extraction, transportation and use
  - Natural Gas
    - \* Cleaner alternative
  - Oil

#### Problems

- Unsustainable - reserves depleting

- Global warming - Enhanced greenhouse effect by earth atmosphere

- Greater absorption of long wavelength IR in earth's atmosphere
  - Rising temperature anomaly from 1965-now by about 100mm
  - Global sea level rising
    - Thermal expansion of water
    - Melting alpine glaciers and ice sheets
  - Earlier timing of spring events
  - Poleward and upward shift in plant and animal species
- Solution:  
Clean energy
- Replace existing supply of fossil fuels
  - Use energy more efficiently and judiciously minimizing environmental pollution

### High power

### High energy conversion efficiency

### Singapore

Singapore uses LNG primarily (95%) piped from Indonesia and Malaysia

Switching to solar and biofuels to reduce reliance

### Energy conservation

- Outdoor LED initiative
- Electric car sharing

## 02. Fundamentals of thermal energy

$$Q = mc\Delta T$$

Q Heat energy supplied

m mass

c Specific heat capacity of material

T temperature change resulting from heat energy

$$Q = mL$$

Q Heat energy supplied

m mass

L Specific latent heat of vaporization/fusion

### Types

- Conduction
  - Dominant in solids
  - No bulk motion of matter
  - Heat flows from region of high temperature to region of low temperature
- Convection
  - Dominant in fluids (liquid and gases)
  - Works by circulating fluids and thermal expansion properties of materials
  - Cold fluids sink, warm fluid rise
- Radiation
  - Uneven, black bodies absorb/emit better

### Stefan Boltzmann Law

Power of black body radiation

$$P = \epsilon\sigma T_0^4$$

P Energy absorbed per unit second per unit area via radiation

$\epsilon$  Emissivity of surface (lies between 0-1)

$$\sigma 5.67 \times 10^{-8} = \text{Stefan Boltzmann constant}$$

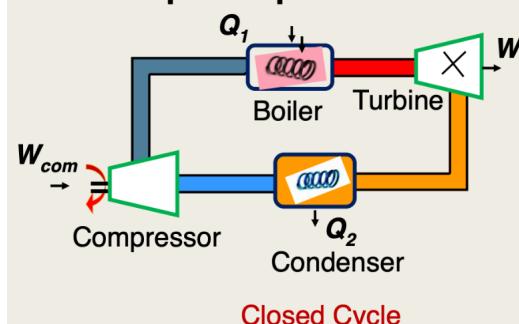
## First law of thermodynamics

Difference between the heat absorbed  $Q$  and the work done  $W$  on object is equal to change in internal energy of the thermodynamic system

$$Q - W = \Delta U$$

### Steam based thermal power plant

### Layout of steam based thermal power plant



#### Key stages

**Compression** Work done on system to compress cold water to high pressure

**Boiling** Heat added to the system to convert cold water into steam

**Turbine rotation** Work  $W_t$  done by the system on turbine blades

**Condensation** Heat lost from the system to the environment in converting steam back to cold water

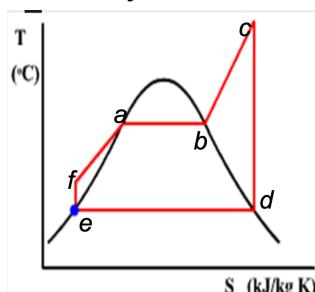
- Working fluid have the same amount of energy U as it had in the beginning of the cycle

$$\bullet \text{Net heat absorbed} = Q_2 - Q_1$$

Efficiency of cycle is given by

$$\eta = \frac{\text{Net output work}}{\text{heat input}} = \frac{W_t - W_{\text{com}}}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

### Rankine cycle



Steam power plant energy generation (Temperature - entropy graph)

- EF - Compressor increases the pressure of water

- FA - Economiser, Water heated at high pressure until it boils

- AB - Evaporator, 2 phase mixture of water and steam is heated at constant pressure until all water converted to dry steam

- BC - Superheater, Dry steam heated at constant pressure in superheater

- CD - Dry steam enter turbine at high pressure and rotate the turbine

- DE - Steam converted to water

- Problem: Unable to completely eliminate the formation of water droplets @ CD

- Solution: Reheat the steam at CD to rotate the turbine again

- Temperature is raised again, leading to greater efficiency

- Achieve 40% efficiency

- Cannot go beyond 650c to prevent metal fatigue

### Brayton cycle

Use gas instead of water leading to no worry of water droplets and can go higher temperatures

## 03. Wind energy

### How wind forms

#### Dominant

- **Coriolis Effect** - Sideward component of wind due to earth rotation

- **Solar radiation** - Warm air rises up in the equator leading to difference in densities

#### Other factors

- Ocean
  - Water absorbs/releases heat slower than land
  - Day: Water less hot, sea - land
  - Night: Water hotter, land - sea
- Surface friction
- Eddy motion
- Seasonal effects

### Power of wind

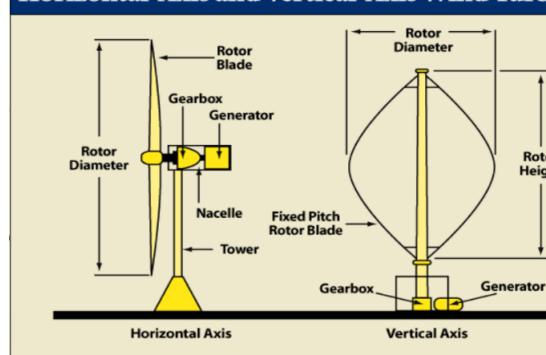
$$P = \frac{1}{2} \rho A v^3$$

Wind speed affected by height of the turbines

- Wind speed rises proportionally to 7th root of altitude

### Wind turbines

#### Horizontal-Axis and Vertical-Axis Wind Turbines



- **Yaw control** - Orientates the nacelle in direction of incident wind

- Note: Better for rotor to face the wind
- Less wind shadowing effect
- Blades flex less
- Less fatigue in the blades

## Forces

**Drag** Net force in direction of wind

**Lift** Net force perpendicular to wind

## Blades

Turbines cause turbulence for surrounding blades so cannot have too many blades

**Tip Speed Ratio (TSR)** -  $\frac{\text{Speed of rotation of outer tip}}{\text{incident wind speed}}$

**Betz limit** - Maximum theoretical efficiency of rotor

**Capacity factor** -  $\frac{\text{yield}}{\text{rated power}}$

Dependent on wind speed

## Offshore vs Onshore

- + Wind speed is faster offshore
- + Less obtrusive
- + Bigger in size
- + CF higher
- Harder to maintain cns in the sea (But easier to build because transportation over water easier)
- Might spoil faster due to seawater

## 04a. Solar Power

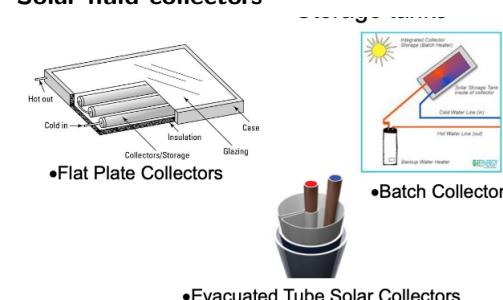
Renewable form of energy with  $3.9 \times 10^{26} W$

Only half reach surface of earth

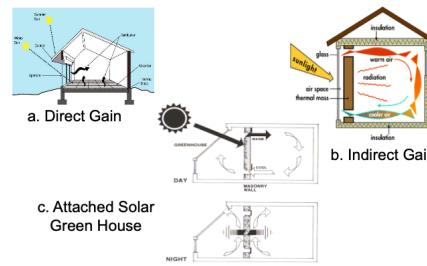
### Types of systems

- **Passive** - Uses no external power
  - Allows fluid heated by the sun to circulate by natural means
- **Active** - Solar heated fluid is circulated by a fan or pump

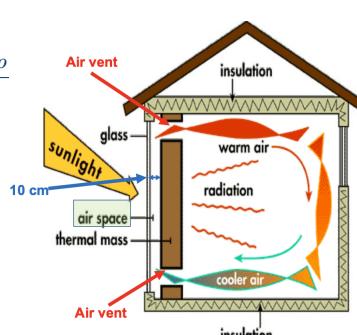
### Solar fluid collectors



## Passive space heating system



## Trombe wall



## Principles of passive cooling

- Minimise solar heat gain
  - Increase building mass
  - Increase thermal protection
  - Reflective coating on exposed surface
  - shading device
  - Air tightness in building
- Remove unwanted heat
  - Evaporative cooling
  - Nocturnal ventilation
  - Thermo-active ceiling

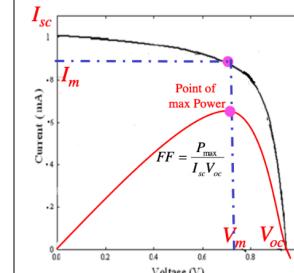
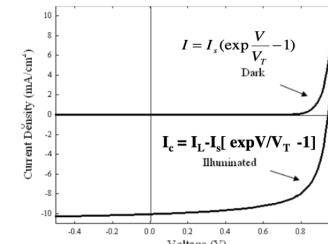
## Solar power energy

- Using the heat by the sun to drive rankine cycle
- using mirrors to focus sun light into a tower to heat molten salt
  - Run focus pipes surrounded by mirrors to heat the fluid in the pipes to be used to generate heat

## 04b. Solar Photovoltaics

$$E = hf = \frac{hc}{\lambda} \quad h = 6.63 \times 10^{-34}, c = 3 \times 10^8$$

### Solar Cell Current-Voltage (IV) Characteristics



## Band gap

Minimum energy that is required to excite an electron up to a state in the conduction band where it can participate in conduction  
Higher short circuit current - lower bandgap

## Silicon

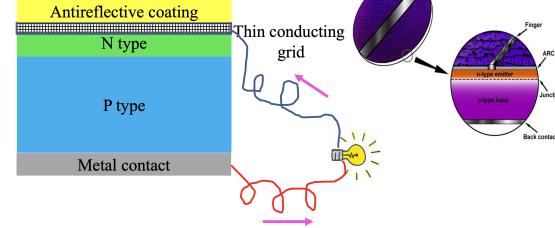
### Types

- Polycrystalline
- Crystalline
- Amorphous

### Mechanism

Transfer of electrons from n-types and p-types to maintain electric potential

- **N-type** - Electron rich (conduct via electrons)
  - Doped with elements with more valence electrons (P)
  - Cathode (negative terminal where current flows into when illuminated)
- **P-type** - Electron deficient (conduct via holes)
  - Doped with elements with less valence electrons (Al)
  - Anode (positive terminal where current flows out of when illuminated)
- Pink arrow denotes conventional current



## Efficiency

- 23% of photons has less energy than bandgap
- 30% heat energy and 10% loss from electron hole-pair recombination
- Increase efficiency by using anti-reflective coating
- Smaller bandgap - greater photocurrent but decrease output voltage (optimum 1.4eV gap)

## 05a. Hydro power

### Ocean vs River

#### River

1. Hydroelectricity

#### Ocean

1. Tidal power
2. Wave power
3. Ocean thermal

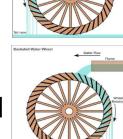
### Water wheels

#### Water mills

- Ancient application for replacing physical labour
  - Replaced with water turbines for energy generation
- Types of water wheels



#### Overshot Water Wheel



#### Backshot Water Wheel

- Undershot
  - Vertically mounted with water flowing at the bottom of the wheel
  - Cheapest and least efficient
- Overshot
  - Falling water on the top of the wheel in direction of rotation
  - Use all water flow for power production
  - Does not require rapid flow of water
  - Uses the difference in weight between the 2 sides of the wheel to turn
- Backshot

- Introduced behind the apex of the wheel
- Water flows opposite the direction of rotation
- Continues to function even when water in wheel put rises beyond height of axle
- Technique useful for streams that experience extreme seasonal variations in flow

## Types of Hydro Power

- Dam based
- Run of the river plants(diversion)
- Pumped storage technology
- Damless hydro power

## Principles of power generation

Production of electricity by using gravitational force of falling water

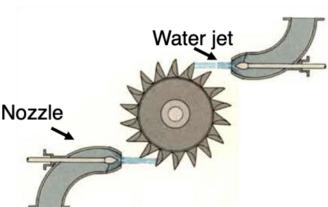
$$P = \eta \rho g h Q$$

$\eta$  = efficiency,  $\rho$  = density of water,  $Q$  = Volume of water flowing per second on turbine,  $h$  = Vertical distance between turbine and water surface

## Types of water turbines

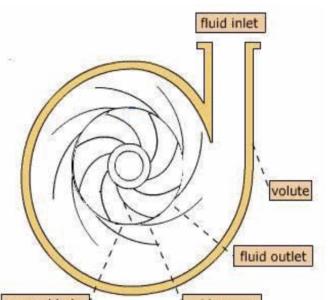
### Impulse

- Simpler and cheaper design - Easier to fabricate and maintain
- Needs higher head height
- Higher volume flow rate
- Greater tolerance of sand and other particles in water
- Better access to working parts



### Reaction

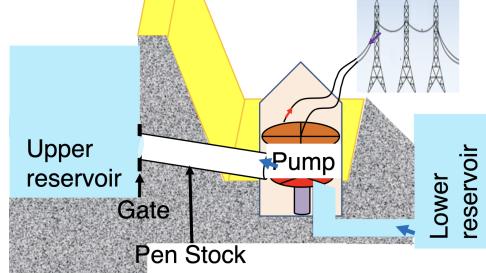
- Rotating element in reaction turbine enclosed in pressure casing to generate energy
- Rotates faster than impulse turbines given same head and flow conditions
- More expensive



## Run of the river

- Low-level diversion weir/stream bed instead of dam
- Located on fast flowing, non seasonal stream
- Minimize impact on environment

## Pumped Storage Hydroelectricity



## Pumped storage hydro

- Load balancing by storing energy pumped from lower elevation reservoir up
- Low cost off peak power to run pumps and released when high demand
- Net consumer of energy but largest capacity form of grid energy storage

## Damless hydro

- Little to no maintenance
- Low initial setup cost and environmental impact
  - No risk of flash flooding/dam-related accidents
  - No silt accumulation and fish ladders

## Advantage of hydroelectric

- Clean renewable energy (Low level of greenhouse gases)
- Low operating cost and highly automated
- Plant life is long  $\approx 40$  years
- Available on demand as flow rate is controlled

## Problems with hydroelectric

- Capital cost is high and payback time is long
- Social issues with displacement of population
- Environmental impact (Diversion of water)

## 05b. Ocean Power

### 1. Tidal energy

- Gravitational field of sun and moon
- Ocean wave energy
- Ocean thermal energy

### Tidal energy

- Derived from gravitational interaction between Earth and Moon
- Bulge on opposite side due to earth's attraction
- Low and high tide occurring simultaneously at 2 places with longitudes differing by 90°
- Interval between high tides approximately 12h
- **tidal range** - Difference between height of high and low tides
- **Spring tides** - Moon and sun align leading to unusually high tides
- **Neap tides** - Moon perpendicular to sun wrt earth leading to weak tides

## Tidal barrage

- Dam built across river estuary
- High tides: Seawater flows into reservoir of barrage and rotate the turbine blades
- Low tides: Seawater stored in barrage is allowed to flow back out into sea turning turbines
- Output power  $P = \frac{\eta \rho g A h^2}{T}$

-  $T$  is tidal period (time interval between 2 successive high tides)

## Advantages

- Free, reliable and green (low maintenance)
- Turbines are cheap and do not cause large environmental impact

## Disadvantages

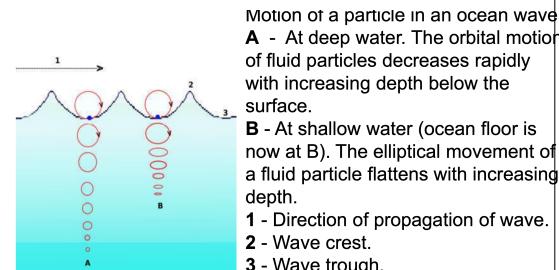
- Only provides power for about 10 hours each day (when tides moving)
- Tidal barrage sites are limited
- Fish ladders have to be installed and total cost is expensive

## Ocean current and waves

- Horizontal movement of seawater in the ocean
- Factors affecting:

- Intensity of solar radiation
  - \* Fast moving air from sea surface to land
  - \* Water dragged along the wind
- Air temperature
- Wind speed and direction
- Gravitational pull of sun and moon

### • Moving up and down in circles



## Types of devices

- Oscillating water column devices
  - Traps air which increases and decreases in volume as the sea surface moves up and down
- Buoyant moored device
  - Floating on surface of water and rotate to generate electricity
  - Requires depth of 80m with almost constant tension to mooring cables
- Archimedes Wave Swing

- Hydraulic system that compresses air within cylinder when pressure on top of cylinder increases (crest approaching) and vice versa
- Only one moving part so more reliable with less maintenance
- Pelamis (Hinged contour device)
  - Semi submerged construction generating power from motion at joints
  - Rocking back and forth with waves activates hydraulic pumps driving electricity generators

## Impacts

- Large global potential
- Destroys scenic beauty and generates noise pollution
- Have to withstand extreme weather conditions at sea

## Ocean Thermal Energy Conversion (OTEC)

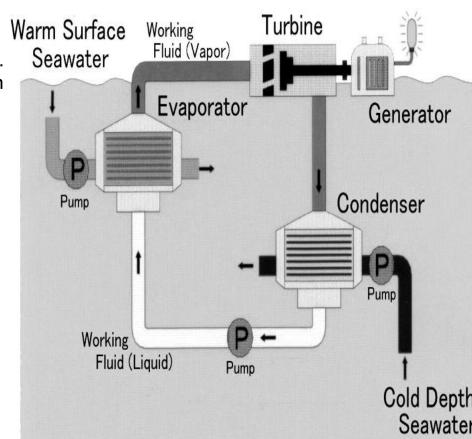
- Using heat energy stored in oceans to generate electricity (best  $\approx 20$ c at 1000m)
- Difference in high[shallow] and low[deep] temp to rotate turbine
- Uses rankine cycle (closed/open/hybrid cycles) in low-pressure turbine and ammonia

## Benefits

- Provides air conditioning for buildings and refrigeration
- Rich in mineral - used for aquaculture
- Production of fuels concurrently (hydrogen, ammonia and methanol)

## Concerns

- Marine organism entrainment and impingement from water current
- Chemicals used to reduce/control biofouling buildup
- **Upwelling** - Rise of deep cold water to surface



## 06. Biofuels

- Plant and animal derived materials that are renewable and carbon neutral
- Efficiency of photosynthesis  $\approx 0.5\%$
- Items: Corn, soy, sorghum, sugar cane, waste, sawdust
- Low energy content per kilogram and low density - bulky and expensive

## Methods of conversion

### Thermochemical

1. Direct conversion
    - Burning solid biomass and production of thermal energy
  2. Gasification
    - (a) Decompose starting material without oxygen to produce hydrocarbon gases and tar by-product
    - (b) Heat char again with oxygen to synthesize more gases
    - Advantage: Gaseous fuels mix better than liquid and burns more efficiently and cleanly
    - Most economically competitive use of biomass
3. Pyrolysis
  - Liquefied by heating in the absence of air

### Biochemical

1. Anaerobic digestion
  - Decomposition of organic matter in the absence of air by bacteria
  - Occurs naturally at 30-60°C producing methane for heating, cooking and powering generators
  - **biogas** - Methane and CO<sub>2</sub>
2. Fermentation
  - Using yeast or bacteria to convert to ethanol and CO<sub>2</sub>

### Extraction

- **trans esterification** - Reaction with oil using sodium/potassium hydroxide as catalyst to form ethyl/methyl esters (biodiesel)

### Impact

- Energy security since biomass is more evenly distributed over earth's surface
- Rural economic growth
- Good and easy storage options

## 07. Geothermal

- Energy extracted from heat stored in the earth
- Formation of the planet, radioactive decay of mineral, volcanic activity and from solar energy absorbed by surface
- Flowing from the hot core by conduction and convection
- Dissipates to atmosphere and space
- Strongest along tectonic plate boundaries

### Methods

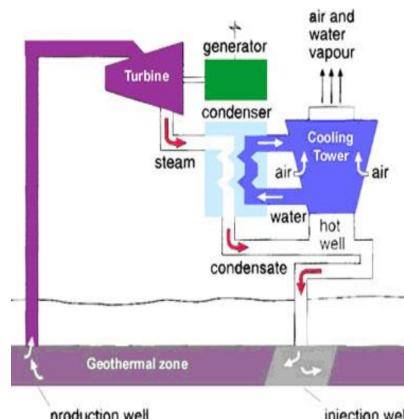
1. Borehole heat exchangers
  - Heat extraction from ambient rock formation
2. Hydrothermal systems
  - Heat extraction from thermal groundwater
3. Hot-dry rock
  - Water circulation through stimulated fractured rock

## Sources

- Hot springs
  - Gushes of hot water found on land surface
  - Water vapor emission from cooling molten which rises through rocks to condense at surface
- Fumaroles
  - Vents from which volcanic gas escapes into the atmosphere
  - Persistent for decades and centuries
  - Dangerous gas at around 70-100°C
- Geysers
  - Hot spring erupting periodically ejecting a column of hot water and steam

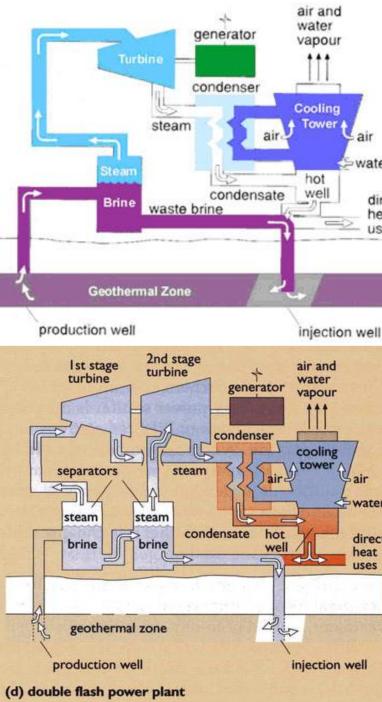
### Extraction

1. Dry steam system
  - 180-225°C, 4-8 MPa at 200 km/h
  - Drive steam generator at 1 kWh/6.5 kg of steam
  - Suitable where geothermal steam is not mixed with water
  - Wells drilled to aquifer and superheated pressurised steam brought to surface at high speeds
  - Efficiency: 30%, simplest and most economical technology



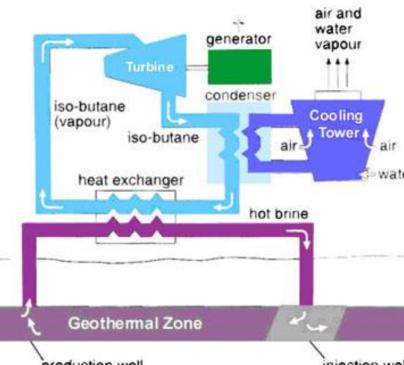
### 2. Flash system

- Steam with water extracted and water flashes to steam when pressure drops suddenly
- Steam separated from water and used to drive a turbine
- Generates 5-100 MW using 6-9 tonnes of steam per hour
- Single or double [More efficient but higher cost] flashed systems



### 3. Binary cycle system

- Used for geothermal resource with low temperatures with liquids with low boiling points
- Liquids boiled to drive turbine which condenses and recycles continuously
- 7-12% efficient
- More expensive but can have higher efficiencies than flash plants



### 4. Geothermal heat pumps

- Storing and retrieving heat from earth using anti-freeze/water solution circulated in plastic pipe loops 200m into ground

### Concerns

- Environmental impacts (tremors, subsidence - sinking of ground)
- Non-steady state source
- High initial capital cost but minimal operating cost

## 08. Nuclear

**Nucleons** Protons and neutrons in nucleus of atom

**Mass defect** Mass difference between sum of masses of nucleons and mass of nucleus

**Nuclear force** Short range and attractive force pulling nucleons together (unless separation very close)

**Binding energy** Energy needed to break nucleus into constituent nucleons

**Mass energy relationship**  $E = \Delta Mc^2$

- $E$  = Binding energy,  $\Delta M$  = mass defect,  $c$  = speed of light in vacuum

### Nuclear Fission

- Bombardment of large atoms by slow moving neutrons resulting in splitting of nucleus into smaller nuclei, neutrons and energy

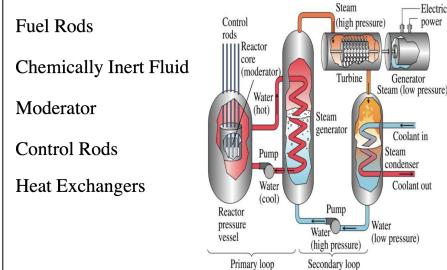
### Chain reaction

- Neutrons released by fission of one atom causing fission of other nuclei
- Dependent on the probability of neutron-induced fission compared to neutron loss
- Behaviour of neutrons after reaction: (dependent on energy of incident neutrons)
  1. Scattering
  2. Capture and induced fission
- Neutron loss arises from neutron capture and gamma ray emissions
- Neutrons have to have low energy to ensure chain reaction (need smaller nucleus U-235 instead of 238)
  - Enrichment is done to increase concentration of U<sup>235</sup>
  - **Moderators** - Nuclei with low atomic number, are added to reduce energy of neutrons on emission
  - **Thermal Neutrons** - Neutrons with low enough energy to cause chain reaction

### Fuels

- U<sup>235</sup> used for fission as it readily undergoes fission after absorbing neutron
- U<sup>238</sup> cannot sustain chain reaction so enrichment by separating my mass (centrifuge)
- **Breeder reactor** - Produce Pu<sup>239</sup> by combining with U<sup>238</sup>, neutron and 2  $\beta^-$

### Thermal Nuclear Reactor



## Mechanism

- Rods contain fuels which are immersed in chemically inert fluids for heating
  - Easy refuelling
- Control rods located above core to control reaction
- Hot fluid pumped through loop and release heat to heat exchanger
- Moderator induces chain reaction

## Loops

### Primary loop

- Energy from fission heat water directly in steam generator through heat exchanger
  - Pressure is high, 15 MPa, 315°C
  - Fluid is radioactive from neutrons in reactor core
- Secondary loop
- Water at relatively low pressure at 5 MPa
  - Steam is formed from heating of water in primary loop

## Maintenance

- High neutron flux causes embrittlement of reactor vessel
- Metal becomes less ductile
- Corrosion in steam generating tubes

## Control

- Neutron decreasing as fuel is burnt - Control rods have to be inserted or removed to maintain reaction
- Adding chemical containing nucleus with high neutron absorption property to alter absorption of coolant (eg. boric acid/burnable poisons)

## Effects

- Long lived actinides by-product arising from successive neutron capture reaction on uranium
- Waste products separated for storage (millenia)
- **Radiation** - Ionisation that breaks molecules apart to give free radicals
  - Damage cells
  - Could come from charged particles such as  $\alpha$ -particles,  $\gamma$ -rays or electrons