Nuclear Fuel Cycle 2011

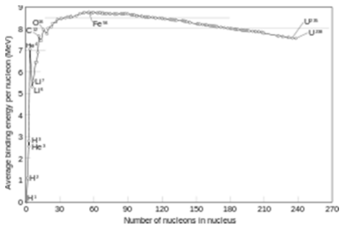
Lecture 8: Reactor Concepts

Binding energy per nucleon

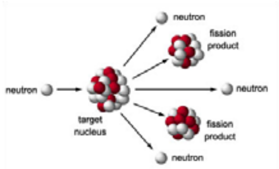
Average binding energy per nucleon (BE/A)

Fission exothermic for A > 60

Fusion exothermic for A < 60



Fission

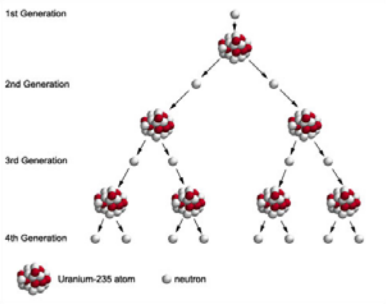


Exotherm process for all nuclides with more than 130 nucleons (A>130)

Activation energy for A=130 is very high; 100 MeV
For A > 230 the activation energy is <10 MeV

Fission with thermal (slow) neutrons is only possible for (even, odd) or (odd, odd) nuclei with Z>90

Nuclear chain reaction



$^{235}U + n \rightarrow$ fission products + 2.4 n + 210 MeV

Fission of ^{235}U with thermal neutrons

Thermal neutron is captured and forms an excited compound nuclueus

$^{235}U + n \rightarrow (^{236}U)^*$

Excitation energy = captured neutron's binding energy (6.8 MeV).
Compound nucleus must emit energy. Either as γ or as fission.
Probability for these can be expressed as cross sections $\sigma_{n,\gamma}$ and $\sigma_{n,f}$

$(^{236}U)^*$ → ($\sigma_{n,f} = 582$ b) → 2 fission products + ν neutrons

$(^{236}U)^*$ → ($\sigma_{n,\gamma} = 101$ b) → $^{236}U + \gamma$

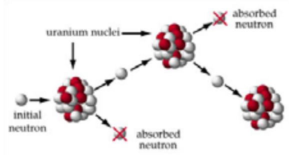
=> 85% of captured neutrons will cause fission

Energy balance

Binding energy/nucleon for heavy nuclei:	7.6 MeV
Binding energy/nucleon for semi-heavy nuclei (A=80-150):	8.5 MeV
Difference:	0.9 MeV
For U-235: 235×0.9 MeV =	**210 MeV**
Kinetic energy of fission products:	175 MeV
Kinetic energy of neutrons:	5 MeV
Kinetic energy of γ:	7 MeV
β from fission products:	7 MeV
γ from fission products	6 MeV
Neutrinos (energy is lost):	10 MeV

Fast and thermal neutrons

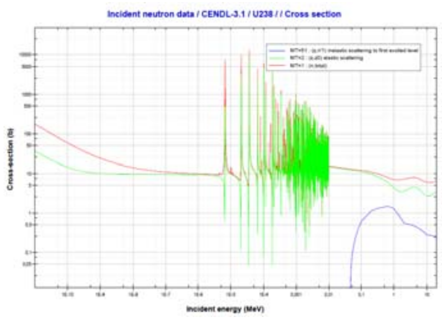
The initial kinetic energy is 5 MeV = **fast** neutron



The kinetic energy will decrease from repeatedly scattering processes

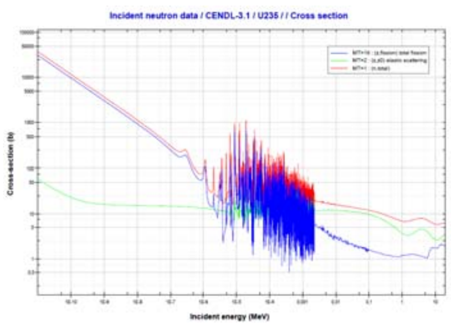
When the energy gain on the average equals the energy loss during a scattering the neutron is called **thermal** (typically 0.0255 eV)

Cross section ^{238}U



Fission only feasible for neutrons with kinetic energy > 0.5 MeV

Cross section ^{235}U



Fission feasible for neutrons thoughout the energy spectra

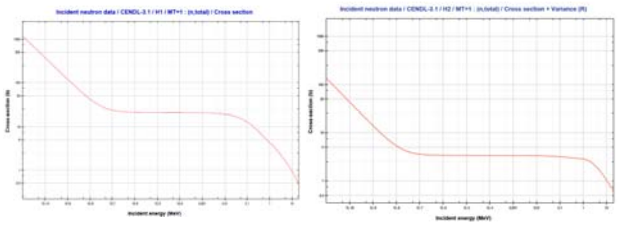
Moderation

Slowing of neutron by various materials

- n denotes the number of elastic scatters to slow down neutron from 2 MeV to 0.025 eV
- L the thermal diffusion length

Material	A	n	L (cm)
H	1	18.2	
H_2O	1 & 16	19.8	2.85
D	2	25.1	
D_2O	2 & 16	35.7	170
He	4	42.8	
Be	9	88.1	21
C	12	115	59
^{238}U	238	2172	

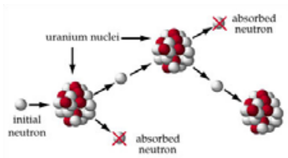
Cross sections for ^1H and ^2H



^1H ^2H

Heavy water corresponds to a longer diffusion length

Effective neutron multiplication factor, k



- If the number of produced neutrons, k > 1
  Supercritical => Atomic explosion
- If k< 1 Subcritical=> Chain reaction will die out
- In a nuclear reactor k is controlled to be 1 (critical) with control rods (containing neutron-absorbent)

Void coefficient

A measure how the reactivity of a reactor changes as voids (typically steam bubbles) form in moderator or coolant

A positive void coefficient means that the effect increases as voids are formed. For instance if the coolant acts as neutron absorber all coolant may quickly boil (Chernobyl)

In reactors designed with a negative void coefficient, the reactivity will decrease as voids are formed

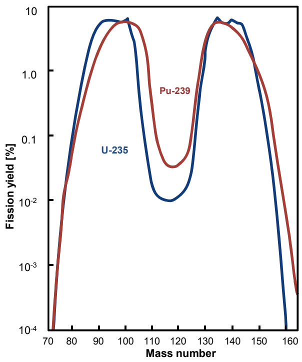
Fission products

Typical distribution between fission fragments for thermal neutron fission of ^{235}U and ^{239}Pu.

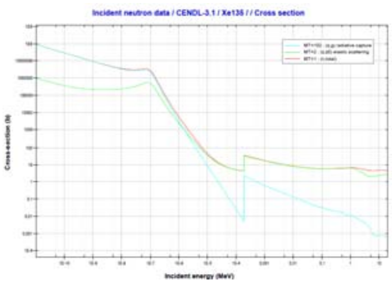
More likely to get fission fragments with mass numbers 90 and 140. The asymmetry becomes less pronounced for increasing bombarding energy

Most fission products are relatively short lived, while some are extremely long lived, i.e. ^{99}Tc ($t_{½}$=211 000y) and ^{129}I ($t_{½}$=15 700 000y)

Even fission products are subjected to neutron irradiation. Some have extreme σ_n, such as ^{135}Xe and ^{149}Sm.



Cross section Xe-135

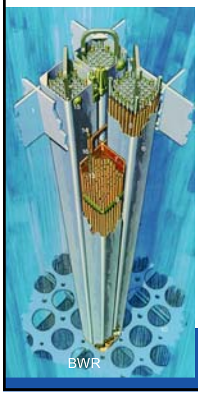


Note: cross sections in the order of 1E7 b !!! (^{235}U < 1000 b)
When the amount of reactor poison are too high, the chain reaction cannot continue and the fuel must be replaced

Main components in Nuclear Reactors

- **The fuel**: Natural U
  Enriched U (>3% ^{235}U)
  Breeder fuel (^{232}Th or ^{238}U)
- **Moderator**: H_2O
  D_2O
  graphite
- **Coolant**: H_2O
  D_2O
  He
  CO_2
  Na or Pb
  Molten salt

Fuel assemblies



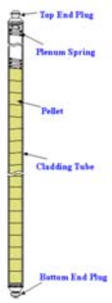
Data	Boiling Water Reactor BWR	Pressurized Water Reactor PWR
Length	4.4 m	4.2 m
Width	0.14 m	0.21 m
Weight	c:a 300 kg	c:a 660 kg
Weight UO_2	c:a 200 kg	c:a 520 kg
Fuel rods	63	204/264
No. fuel assemblies	700	157
Total amount of U in core	120 000 kg	82 000 kg

Fuel rod in LWR

Cladding material: Zircalloy (Zirkonium):
- Hard
- Ductile
- Corrosion resistance
- Low neutron absorption cross section

But above 1000 ºC:
$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$
(ΔH = 586.6 KJ/mole Zr)
which severily accelerates the melting of the core.

Keep in mind:
- a melted core is (in general) not critical (no moderator)
- but has residual heat and will generate even more heat due to oxiditation of Zr, B_4C, SS, etc..



Classification of Nuclear Reactors

Classification by neutron energy: Fast reactors
Thermal reactors
Epithermal reactors

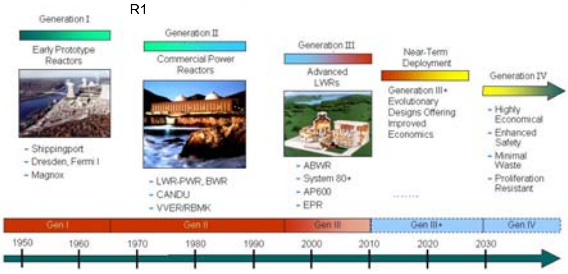
Classification by configuration: Homogeneous reactors
Heterogeneous reactors

Classification by generation: Gen I
Gen II (current reactors)
Gen III (improvements of Gen II)
Gen IV

Classification by use: Research
Electricity production
Heat production
Propulsion
Transmutation
Neutron source
Safety functions
…

Reactor generations

O1, O2, O3
F1-2, F3
R1



Homo- & Heterogeneous Reactors

Homogeneous reactors:
Main parts are one unit, i.e. 235U-salt dissolved in water or molten Li-Be.
Mostly used in research reactors

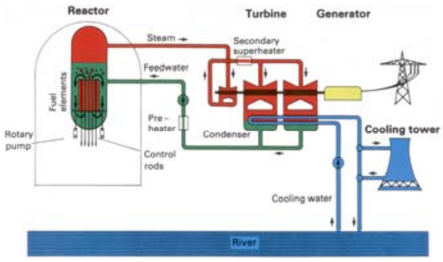
Heterogeneous reactors:
The main parts are divided. Moderator and coolant can be the same.
The fuel is encapsulated and distributed in a certain pattern in the moderator

Principle for a electricity production

- The nuclear chain reaction releases heat
- The heat boils water to steam
- The steam is directed to turbines and electricity is produced

90% of all reactors are BWR or PWR

Boiling Water Reactor (BWR)



Ringhals I
Oskarshamn I, II, III
Forsmark I, II III

BWR design

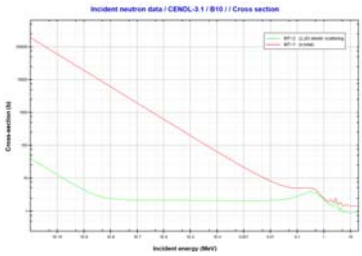
A BWR is designed to have a negative void coefficient

Sudden changes in pressure may cause less voids, leading to increased power.

Reactivity control: Short term – Changing the flow of coolant through the core
Intermediate – Control rods (B_4C)
Long term – Compensate fuel burnup by GdO_2 mixed in fuel pellets

Boron injection used as a safety function

Why Boron?



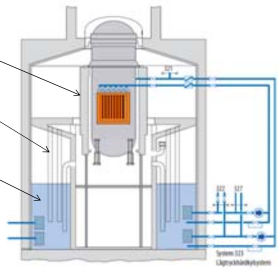
As always, large cross-section, but also highly solvable

BWR containment

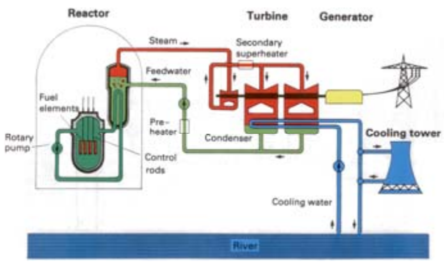
Biological shield

Blow down pipes

Condensation pool



Pressurized Water Reactor (PWR)



Ringhals II, III, IV

PWR design

PWRs operate with no voids. All water is moderator and coolant

Reactivity control: Short term – Control rods (B_4C or Ag-I-Cd)
Intermediate – Varying concentration of boric acid
Long term – Burnable poison in fuel assemblies

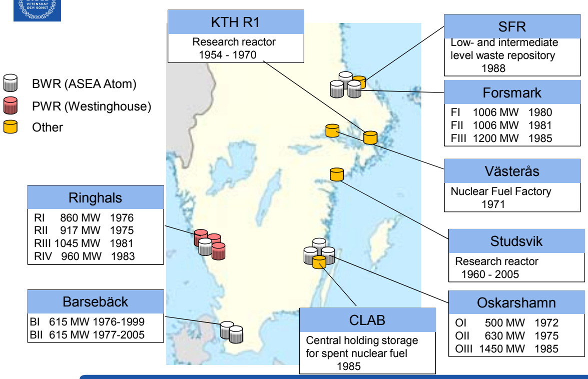
A large negative void coefficient ensures that when voids are formed the power output will decrease

RPW (Reactor Pressure Vessel)

BWR

PWR

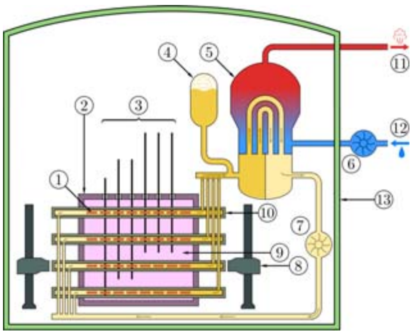
Swedish Nuclear Power System



Other types of reactors

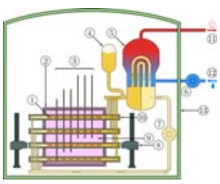
- CANDU (CANada Deuterium Uranium)
- RBMK (High Power Channel-type Reactor)
- Fast breeder reactors

CANDU (CANada Deuterium Uranium)



1. Fuel bundle
2. Reactor core
3. Adjuster rods
4. Heavy water pressure reservoir
5. Steam generator
6. Light water pump
7. Heavy water pump
8. Fueling machines
9. Heavy water moderator
10. Pressure tube
11. Steam to turbine
12. Water returning
13. Containment

CANDU (CANada Deuterium Uranium)



Uses heavy water as moderator (low σ_n)

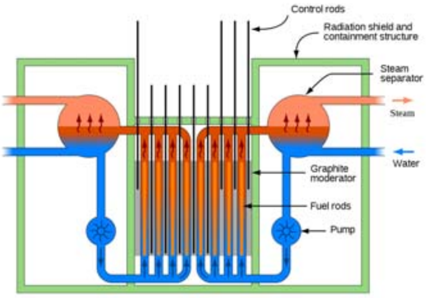
Built with smaller pipes
instead of big pressure vessel

Originally designed to use unenriched U;
Today uses LEU (Low Enriched U)

Positive void coefficient

Cannot operate if the channel geometry is significantly altered

RBMK (Reaktor Bolshoy Moshchnosti Kanalniy) Реактор Большой Мощности Канальный ”High Power Channel-type Reactor”



Very high void coeff.

Needed to use unenriched U and no D_2O

Graphite moderator

Reactor types currently built

Passive safety functions

- No safety-classified pumps or diesel power
- Westinghouse AP 1000
- General Electric ESBWR
- Areva Kerena

Evolutionary reactors

- Continuation of previous development
- Toshiba ABWR
- General Electric/Hitachi ABWR
- Areva EPR (Finland’s Oikiluoto 3)

Main Safety features: Severe accidents
Airplane crash

AREVA EPR

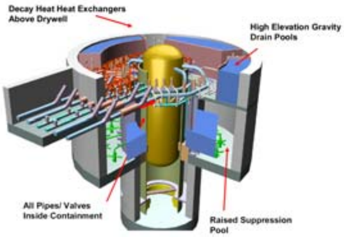
1600 MW

Separated subsystems

General Electric ESBWR

Natural heat convection instead of circulation pumps

Water pools above the reactor

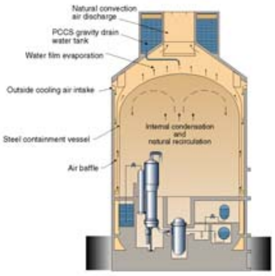


Passive safety functions AP1000

Again, lots of water

Steel containment to improve heat conduction

Internal condensation and natural recirculation



Breeding processes

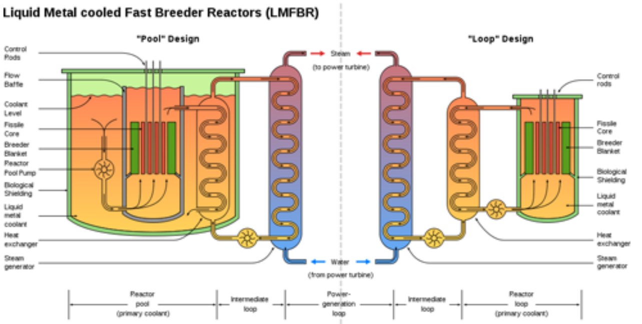
The Thorium-Uranium cycle

$$^{232}Th(n,\gamma)^{233}Th \xrightarrow[t_{1/2}=23m]{\beta^-} {}^{233}Pa \xrightarrow[t_{1/2}=27d]{\beta^-} {}^{233}U$$

The Uranium-Plutonium cycle

$$^{238}U(n,\gamma)^{239}U \xrightarrow[t_{1/2}=23m]{\beta^-} {}^{239}Np \xrightarrow[t_{1/2}=2.3d]{\beta^-} {}^{239}Pu$$

Breeder reactors



Breeder reactors

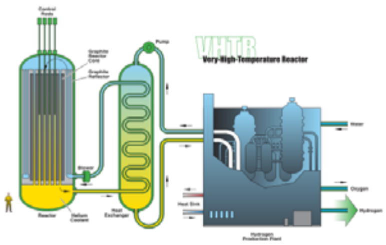
Cooled by liquid metals; Na, Pb, Hg, NaK-alloy (He planned)

Fast neutrons are captured => No need for moderator

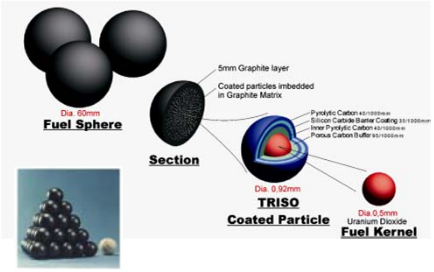
Water not wanted since
- Much water would be needed
- Water moderates neutrons which prevents breeding of U-238 to Pu-239

Generation IV: Thermal reactors

VHTR: Very High Temperature Reactor



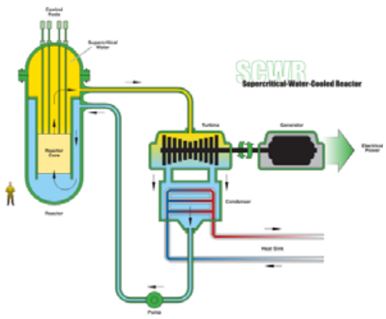
PBMR (Pebble Bead Modular Reactor)



Helium cooled..360 000 billiard balls

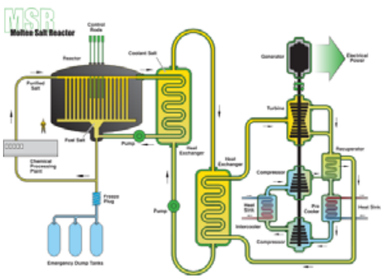
Generation IV: Thermal reactors

VHTR: Supercritical Water Cooled Reactor



Generation IV: Thermal reactors

MSR: Molten Salt Reactor

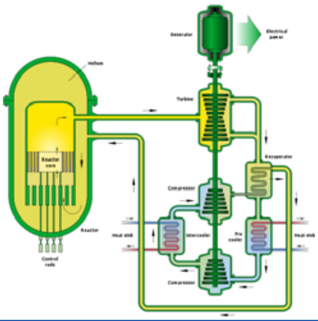


+Better neutron economy
+Small
+Long re-fueling intervals
-Corrosion
-Compicated removal of fission products

Difficult to license radical different reactor designs compared to standard LWR

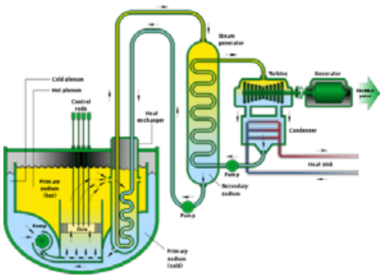
Generation IV: Fast reactors

GFR: Gas-Cooled Fast Reactor

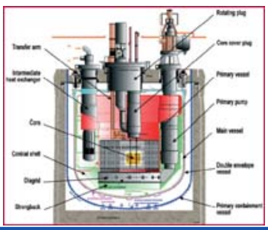


Generation IV: Fast reactors

SFR: Sodium-Cooled Fast Reactor



Phenix



Phenix fast breeder nuclear reactor

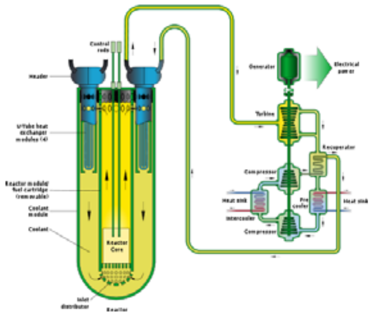
•233 MW
•Breeding ratio 1.12 (12 % more plutonium produced than consumed)
•Shut down 2009

”It’s like riding a bicycle”

Followed by the subsequent full-scale prototype Superphénix (1994-1995)

Generation IV: Fast reactors

LFR: Lead-Cooled Fast Reactor



Gen IV: Pros & cons

+ Nuclear waste that lasts for decades instead of millennia
+ 100-300 times more energy yield from same amount of fuel
+ Possibility to consume existing waste for energy production
+ Improved safety

- Operators have little experience
- Advanced technology more difficult to handle

FUSION?

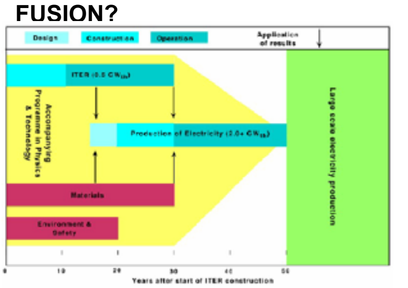


Figure 11.9—ITER project office magnetic fusion roadmap, December 2003

Seems always to be 50 years from large scale production

Reactor safety

Absolutely safe: Does not exist

Inherent safe: Melt down not possible due to nature laws

Structurally safe: Dense containment, filters hinder any release at melt down

Structurally unsafe: Lack dense containment, and any release limiting arrangements

↓

RBMK: (Chernobyl type)

↑

Inherent unsafe: Reactivity increase when coolant disappears