Nuclear Fuel Cycle 2011

Lecture 8: Reactor Concepts

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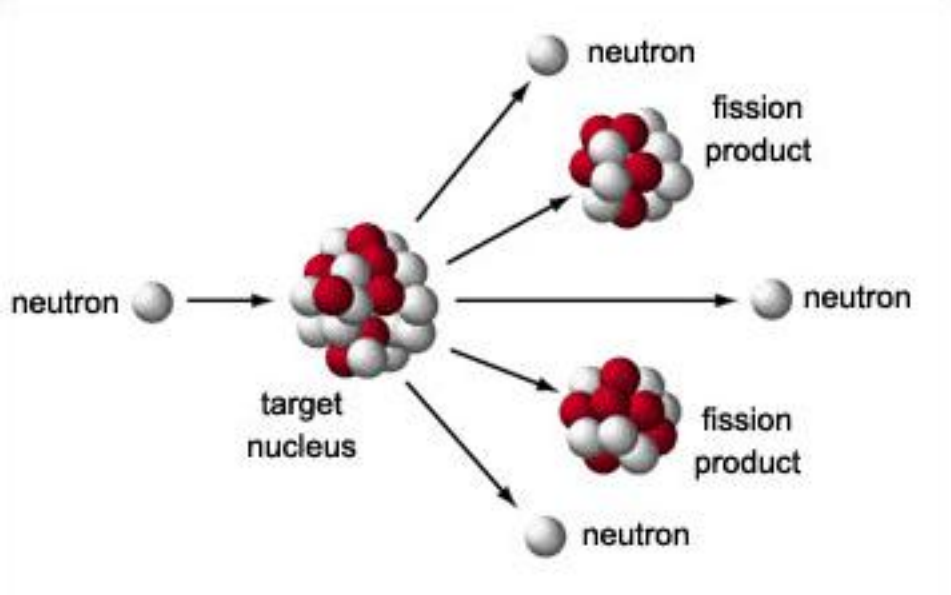
Fission

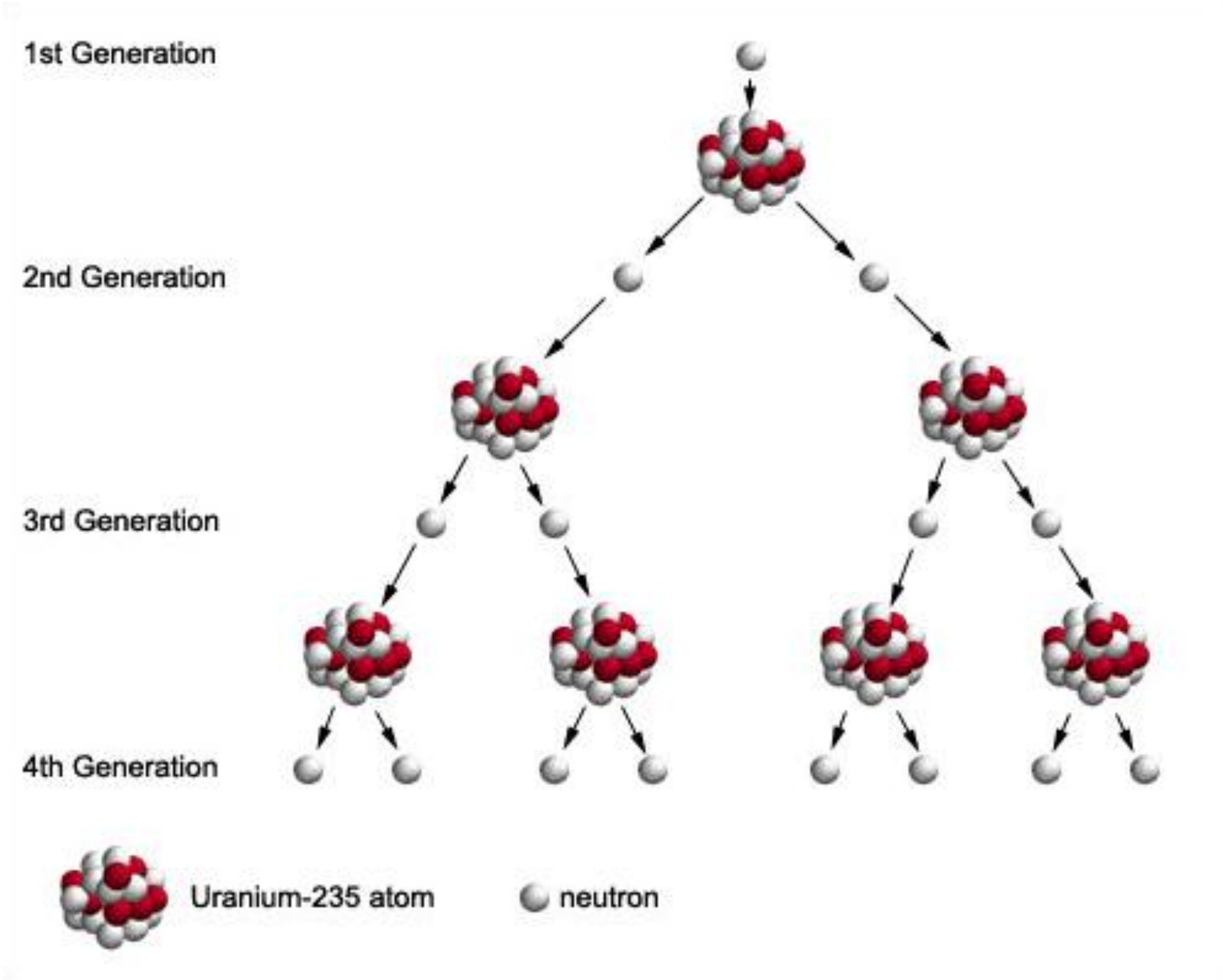


Exotherm process for all nuclides with more than 130 nucleons (A>130)

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



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

Fission of ^{235}U with thermal neutrons

Thermal neutron is captured and forms an excited compound nuclueus

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

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

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

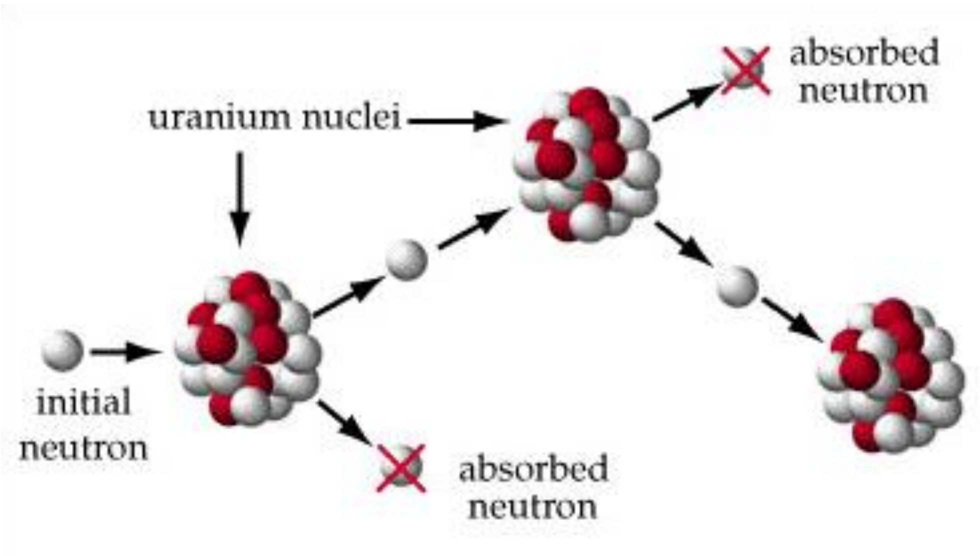
$(^{236}\text{U})^* \xrightarrow{\sigma_{n,\gamma} = 101\ b} {}^{236}\text{U} + \gamma$

=> 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

Effective neutron multiplication factor, k

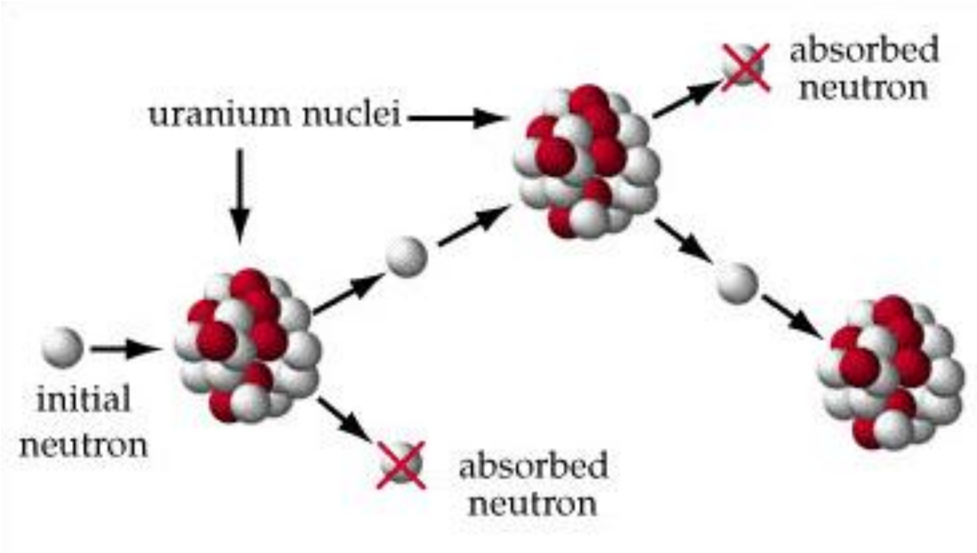


- If the number of produced neutrons, k > 1
  Supercritical => Atomic explosion

- 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)

Moderating neutrons



- Fast and slow (thermal) neutrons are produced. The fast neutrons need to be slowed down A moderator is used for this. The neutrons are slowed down by elastic collisions with the moderator.

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

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

Even fission products are subjected to neutron irradiation
- Some have extreme σ_n, i.e. ^{135}Xe (2.6×10^6b) and ^{149}Sm (41×10^3b)

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, Molten salt

- **Control rods**: Isotopes with high σ_n, such as
  B, Ag, In, Cd, Hf, Dy, Gd, Sm, Er, Eu

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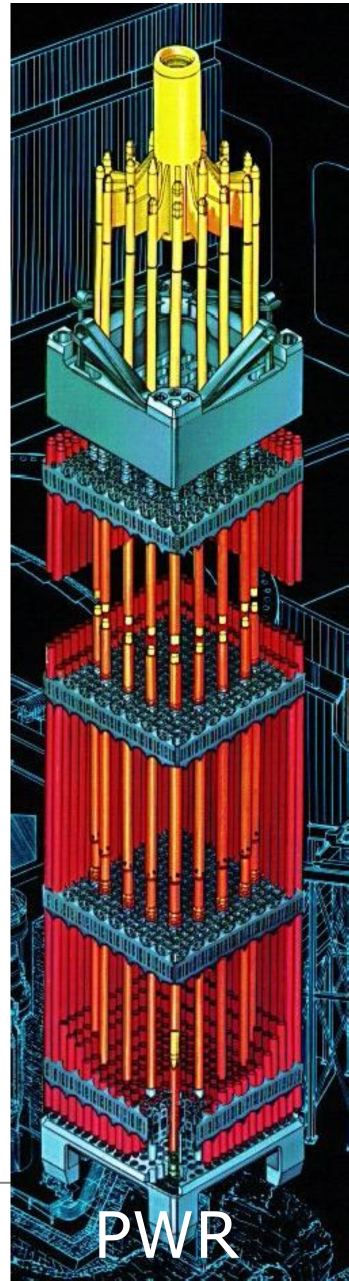
Fuel assemblies

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



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Classification of Nuclear Reactors

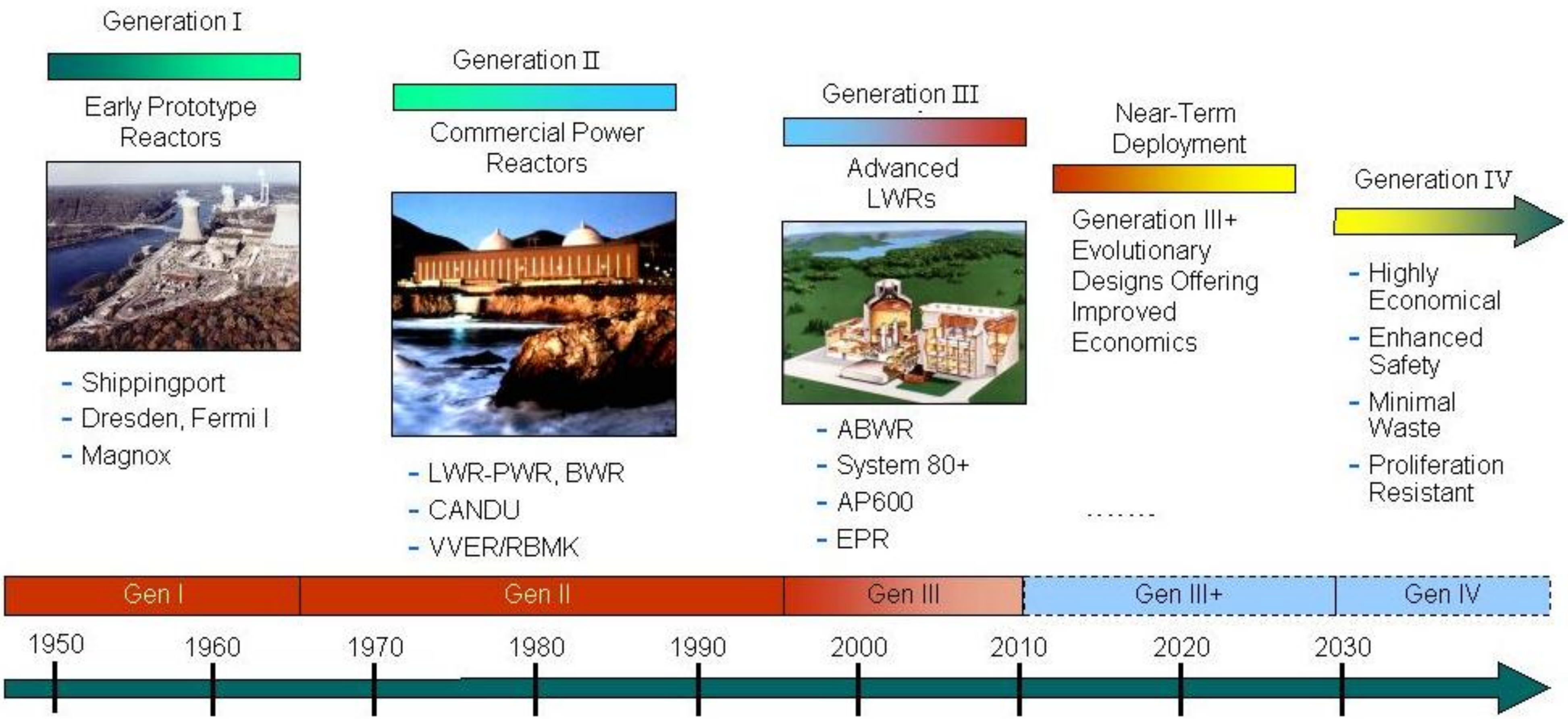
Classification by neutron energy:
- Fast reactors
- Thermal reactors
- Epithermal reactors

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
- …

Reactor generations



Homo-& Hetero-geneous 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

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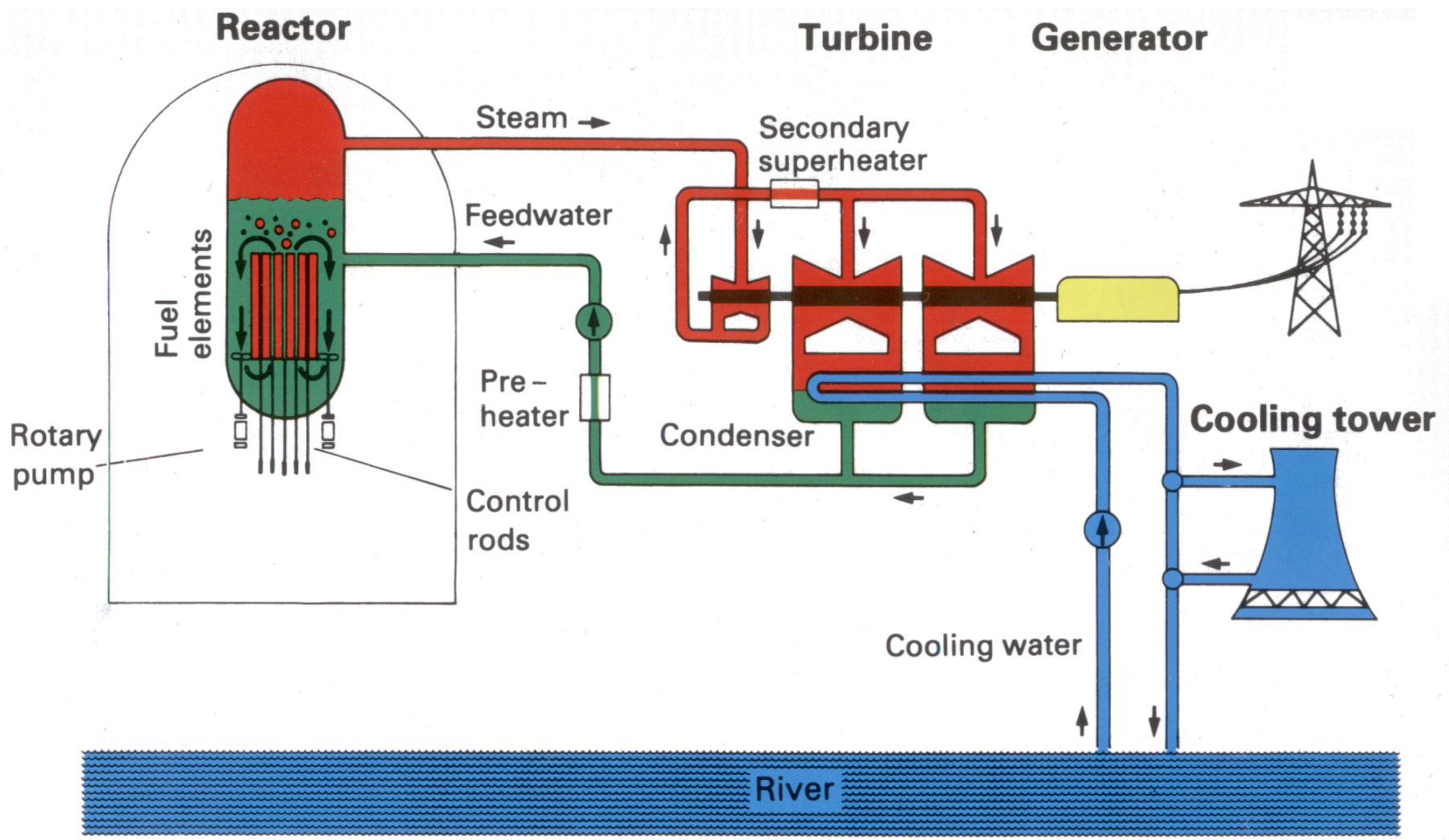
Principle for a electricity production

- 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
Barsebäck I, II

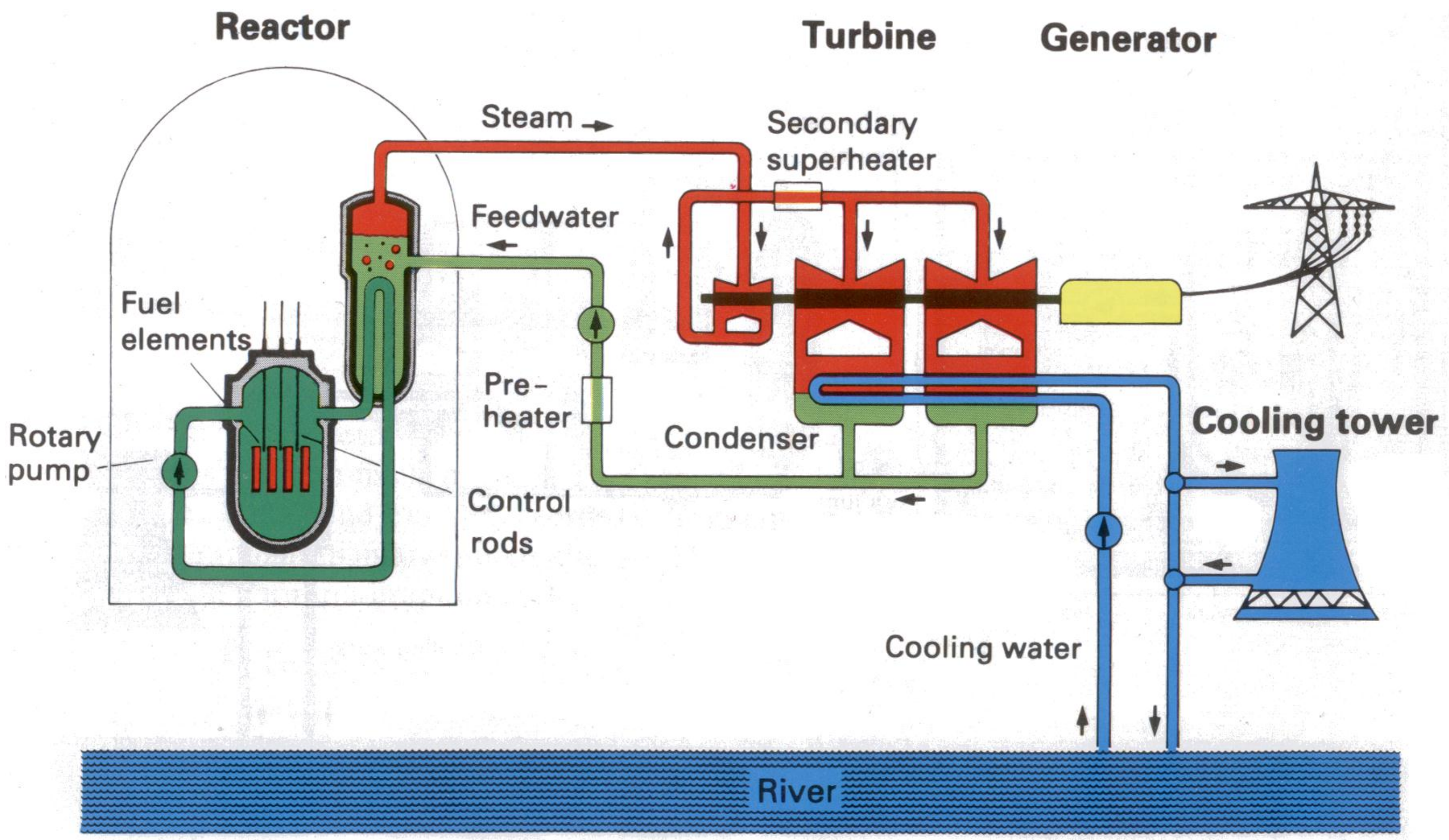
BWR design

A BWR is designed to have a negative void coefficient

At normal operation the reactor power is adjusted by changing the flow of water through the core.

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

Pressurized Water Reactor (PWR)



Ringhals II, III, IV

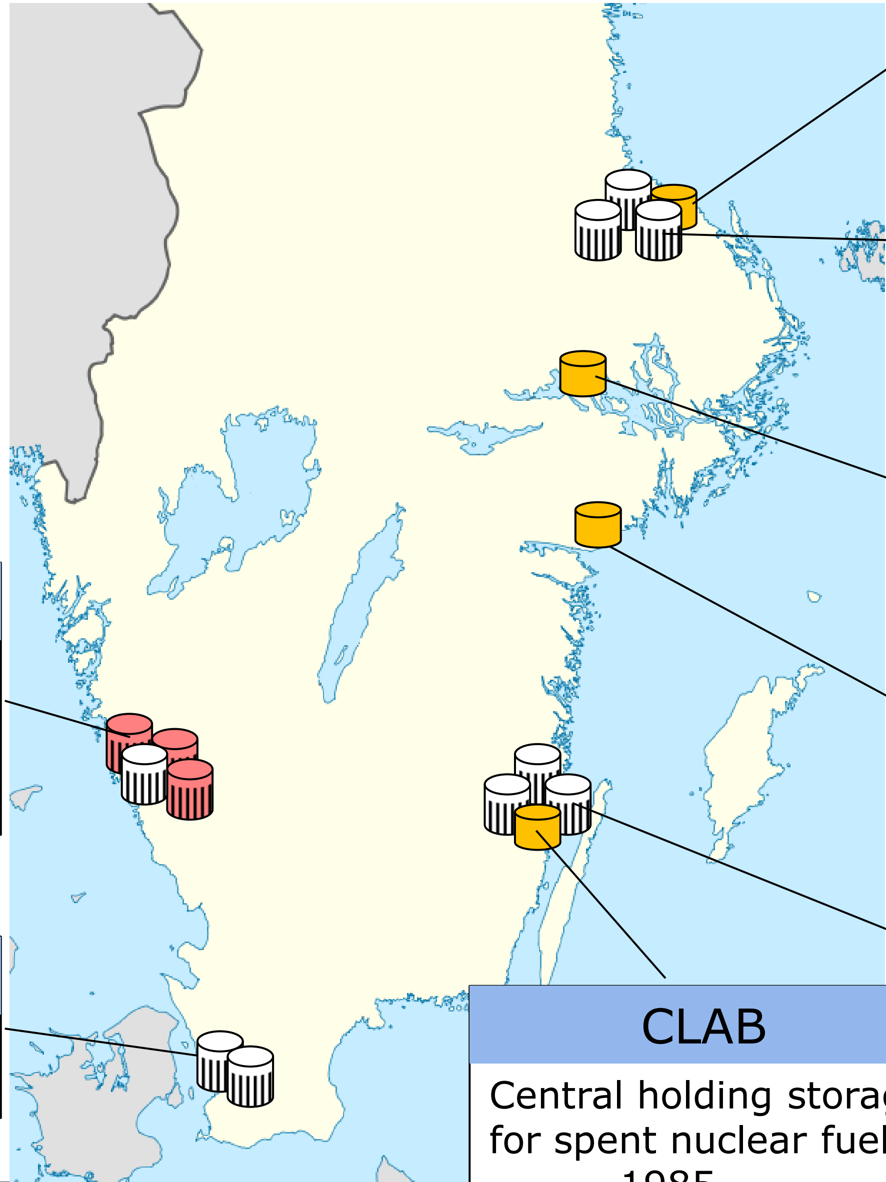
PWR design

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

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

Swedish Nuclear Power System

- BWR (ASEA Atom)
- PWR (Westinghouse)
- Other



SFR
Low- and intermediate level waste repository
1988

Forsmark

FI	1006 MW	1980
FII	1006 MW	1981
FIII	1200 MW	1985

Västerås
Nuclear Fuel Factory
1971

Studsvik
Research reactor
1960 - 2005

Ringhals

RI	860 MW	1976
RII	917 MW	1975
RIII	1045 MW	1981
RIV	960 MW	1983

Oskarshamn

OI	500 MW	1972
OII	630 MW	1975
OIII	1450 MW	1985

CLAB
Central holding storage for spent nuclear fuel
1985

Barsebäck

BI	615 MW	1976-1999
BII	615 MW	1977-2005

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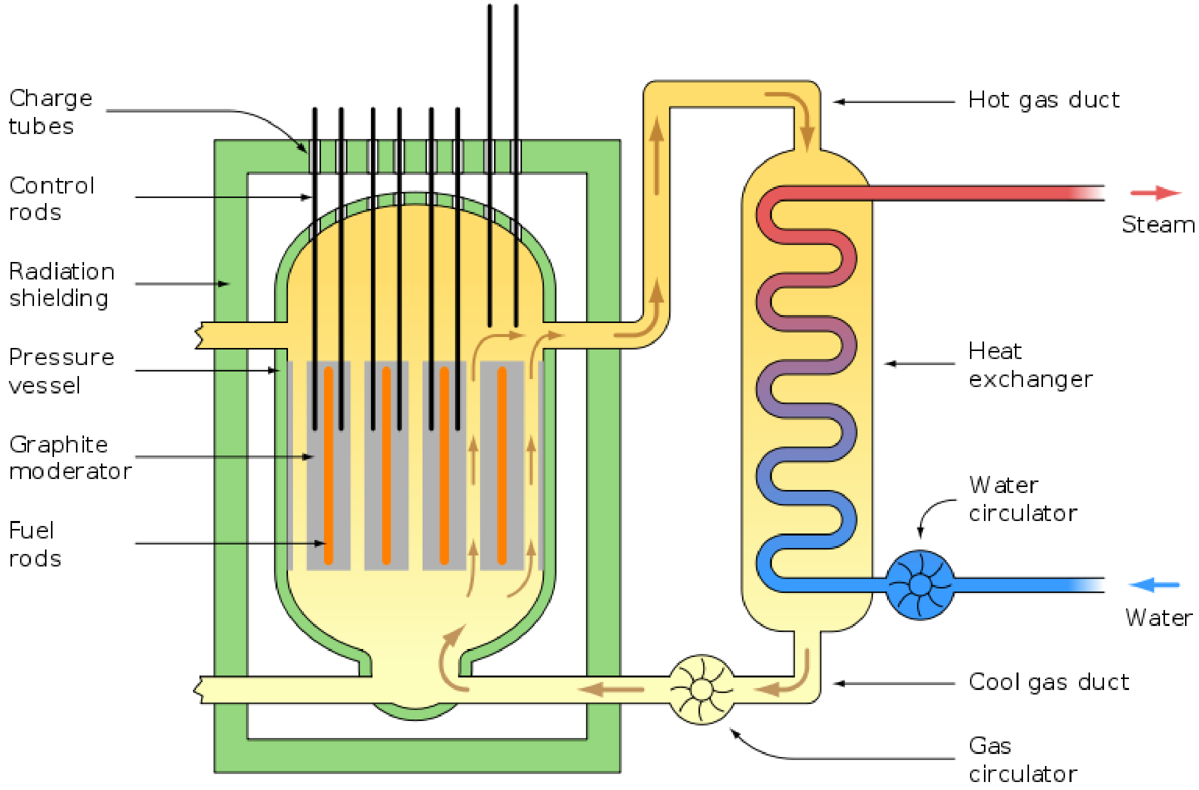
Types of reactors

Reactor type	Numbers	Fuel	Coolant	Moderator
Pressurized water reactor (PWR)	252	Enriched UO_2	H_2O	H_2O
Boiling water reactor (BWR)	93	Enriched UO_2	H_2O	H_2O
Gas-cooled reactor (Magnox & AGR)	34	Natural U, Enriched UO_2	CO_2	Graphite
Pressurized heavy water reactor (PHWR)	33	Natural UO_2	D_2O	D_2O
Light water graphite reactor	14	Enriched UO_2	H_2O	Graphite
Fast Neutron Reactor	4	PuO_2 and UO_2	Na(*l*)	None

Magnox – AGR (Advanced gas-cooled reactor)



Old reactor type from UK, designed to produce nuclear weapons but also produces electricity

Air cooled

If air supply fails the reactor is cooled by natural convection/circulation

The next generation AGR safer

In AGR be refuelled while reactor is working

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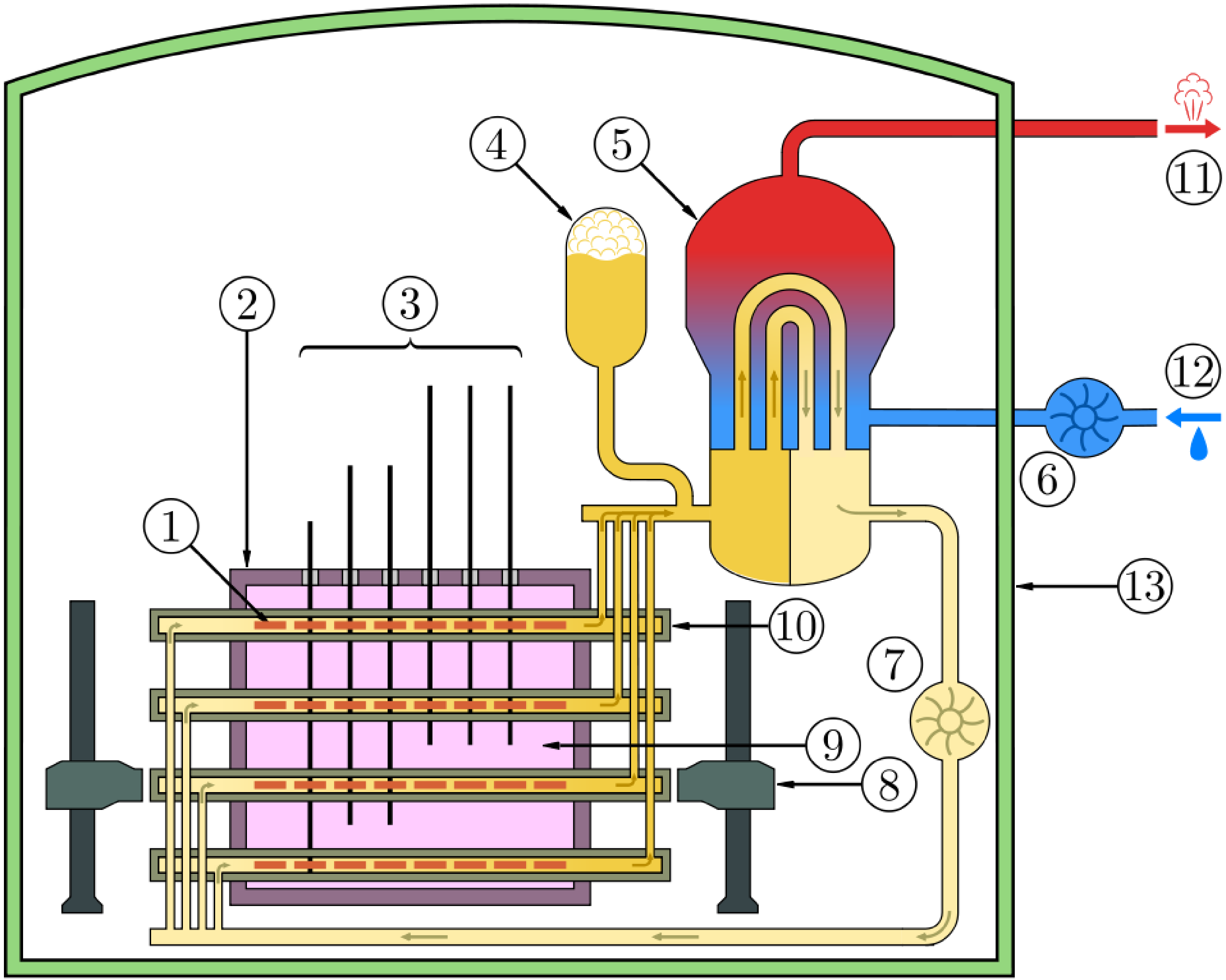
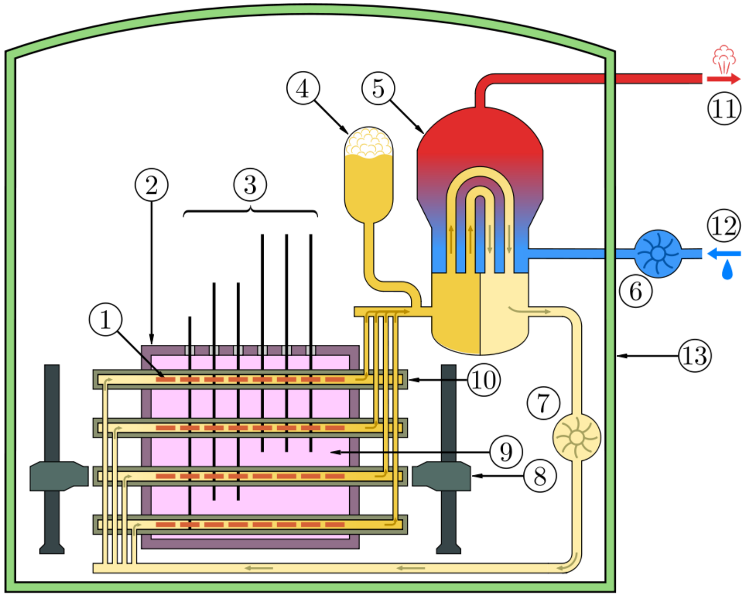
CANDU (CANada Deuterium Uranium)



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

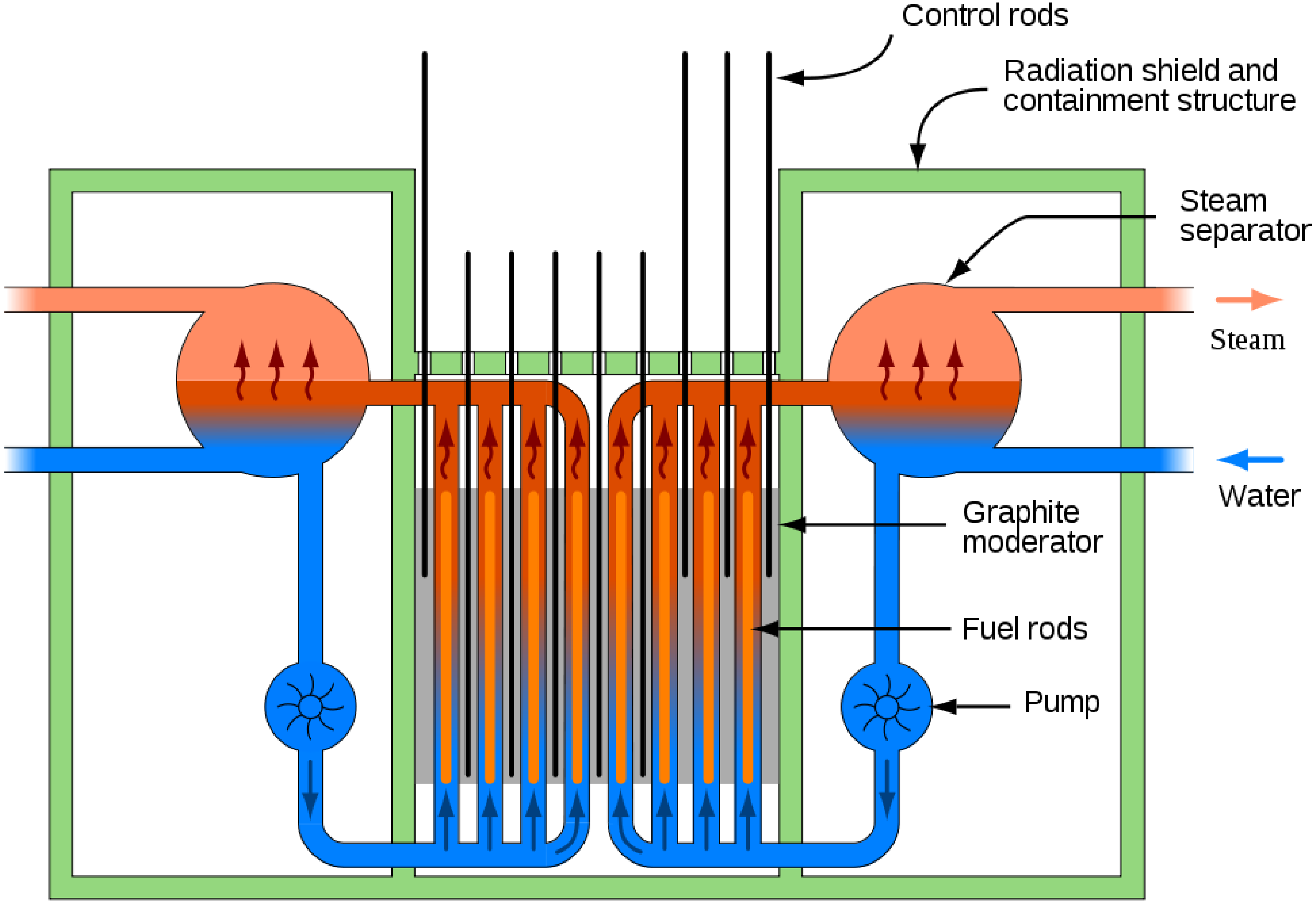
Originally designed to use unenriched U;
Today uses LEU (Low Enriched U)

Can be refuelled without shut-down

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

Breeding processes

Produces more fissile material than it consumes
Breeds fissile material from fertile (U-238, Th-232)

The Thorium-Uranium cycle

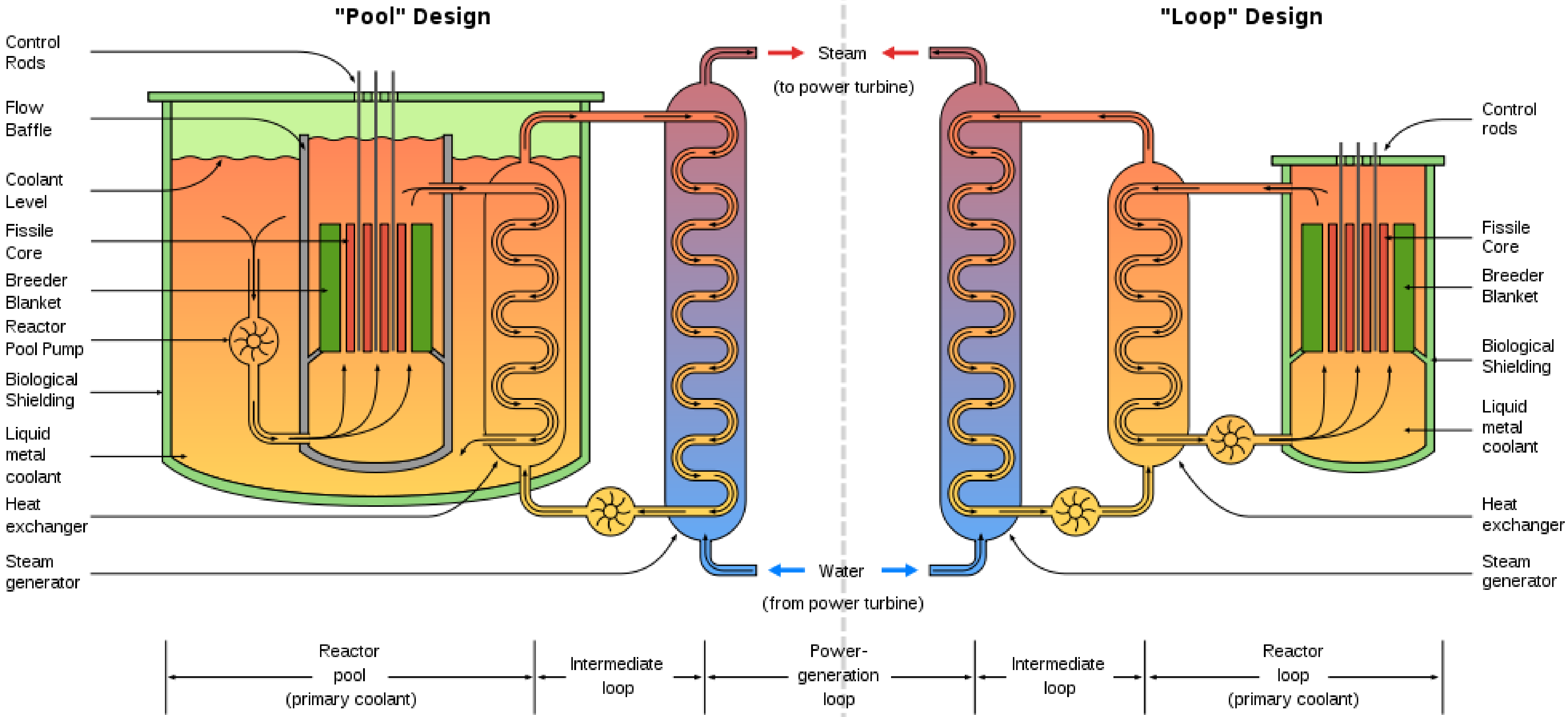
$$^{232}\text{Th}(n,\gamma)^{233}\text{Th} \xrightarrow[t_{1/2}=23\text{m}]{\beta^-} {}^{233}\text{Pa} \xrightarrow[t_{1/2}=27\text{d}]{\beta^-} {}^{233}\text{U}$$

The Uranium-Plutonium cycle

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

Breeder reactors

Liquid Metal cooled Fast Breeder Reactors (LMFBR)



Breeder reactors

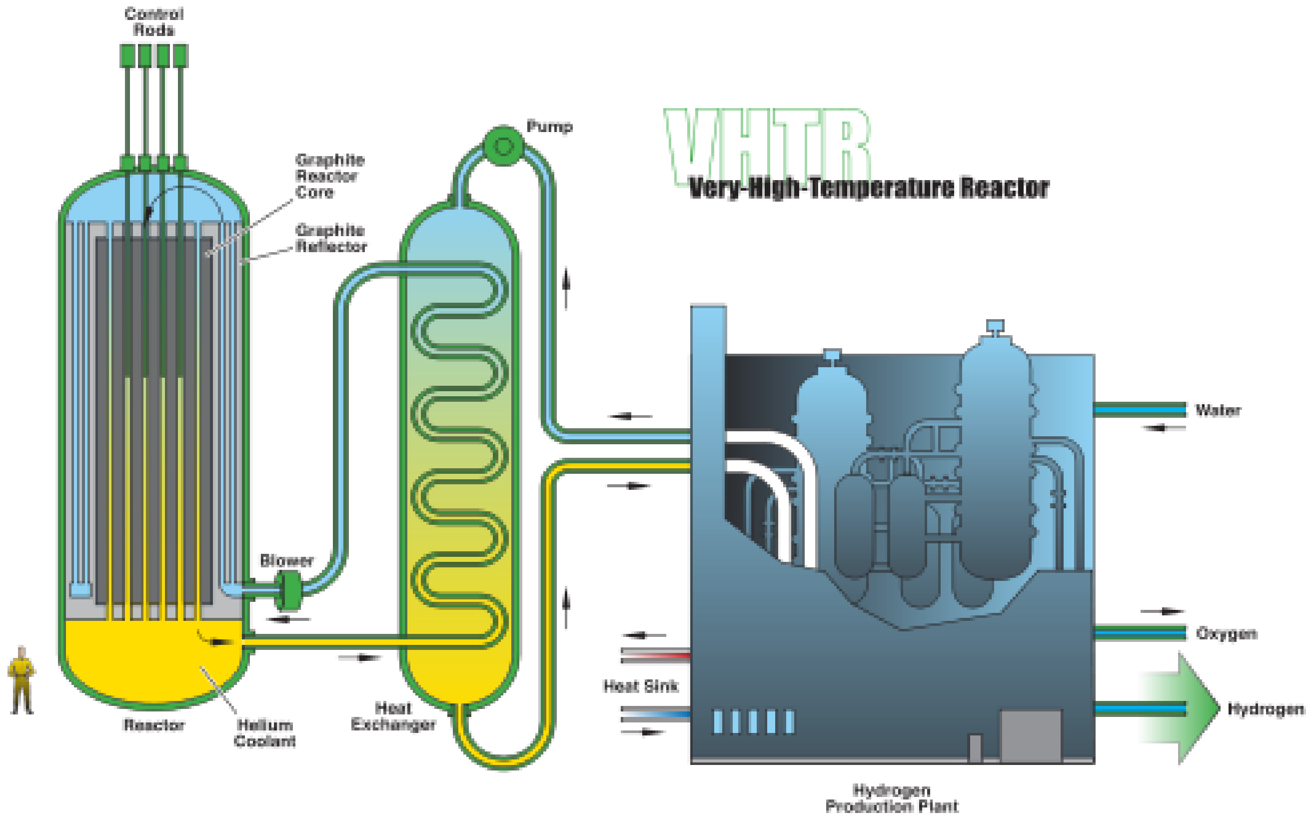
Cooled by liquid metals; Na, Pb, Hg, NaK-alloy (He planned)

Fast neutrons are captured => No need for moderator

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

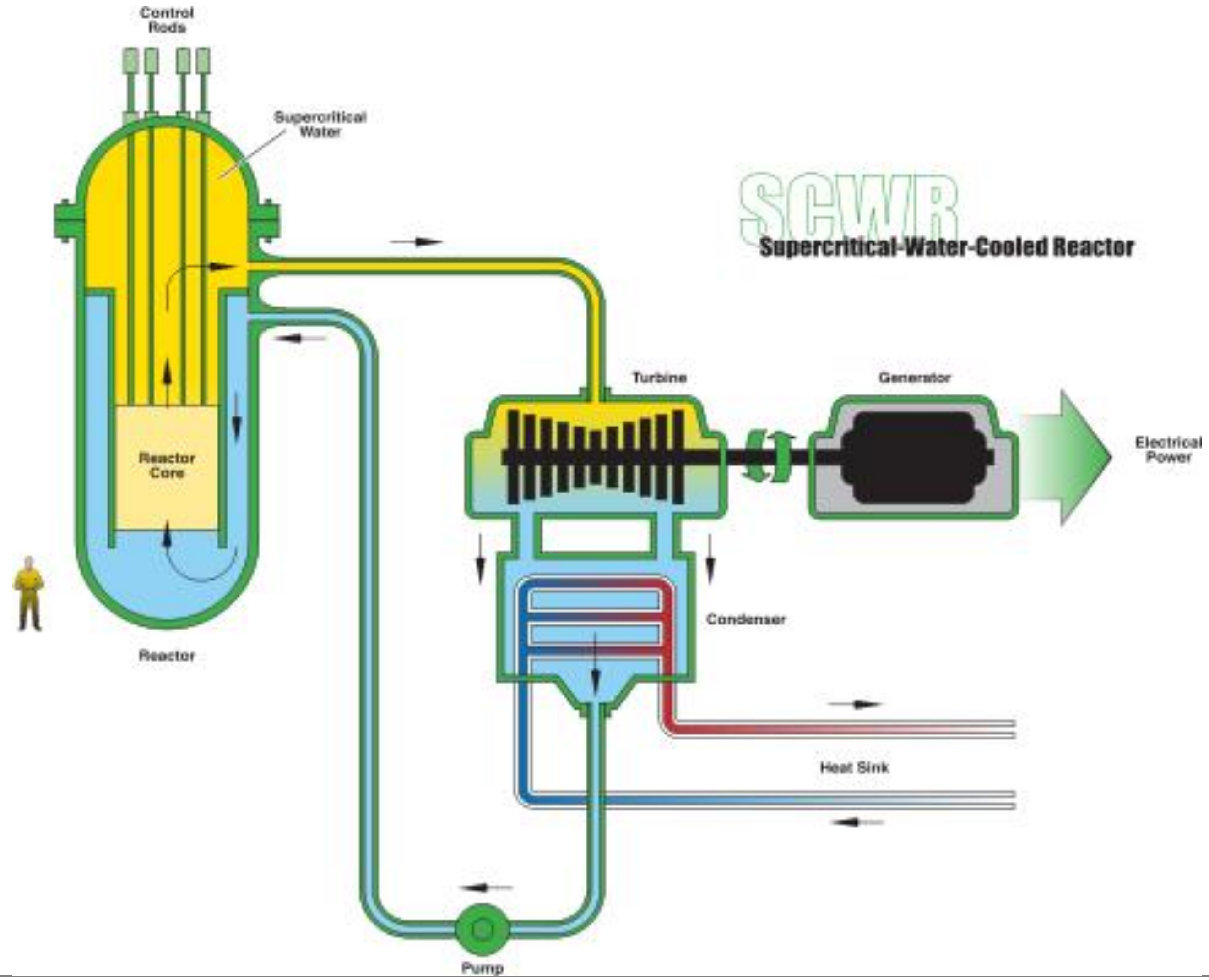
Generation IV: Thermal reactors

VHTR: Very High Temperature Reactor



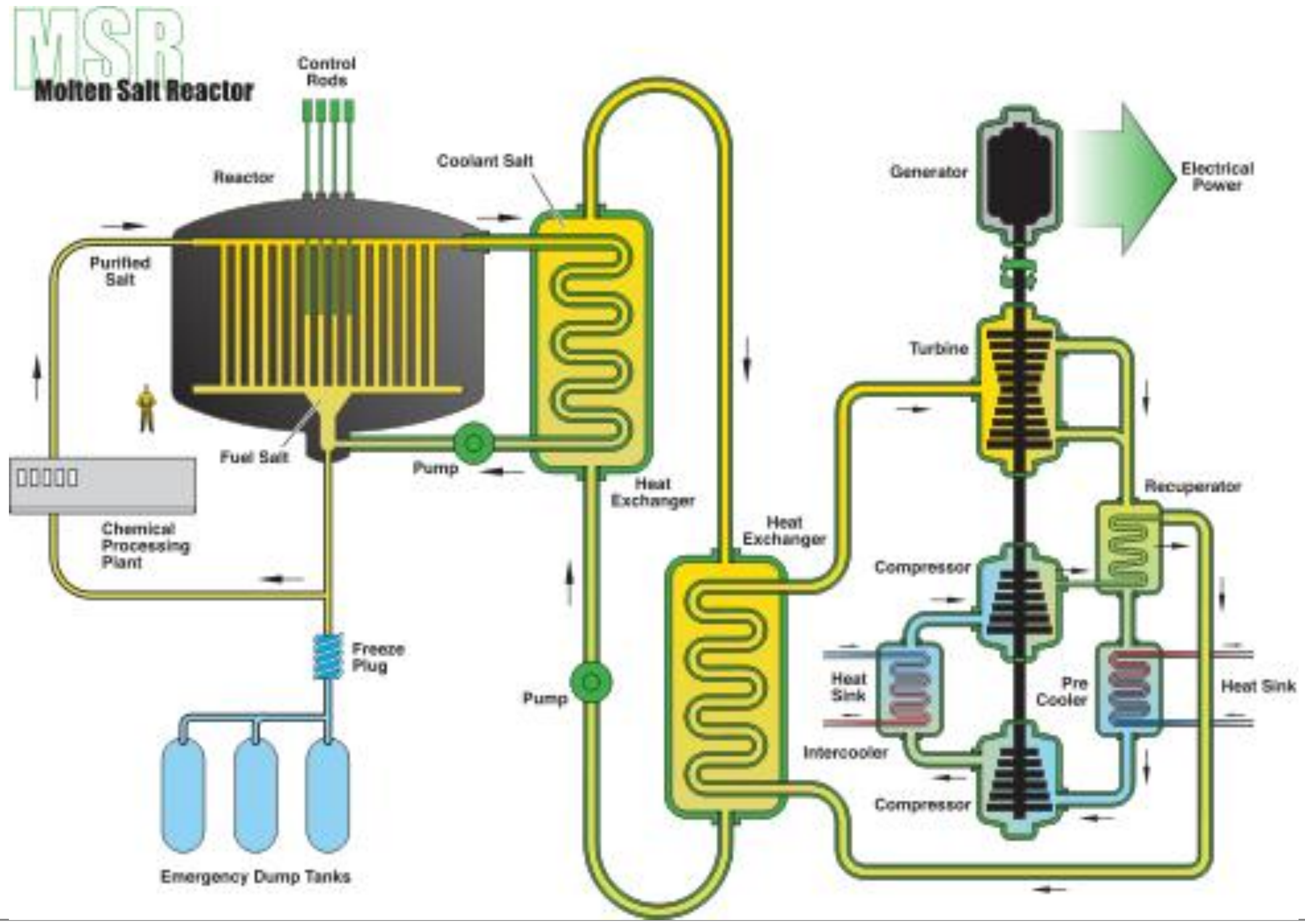
Generation IV: Thermal reactors

VHTR: Supercritical Water Cooled Reactor



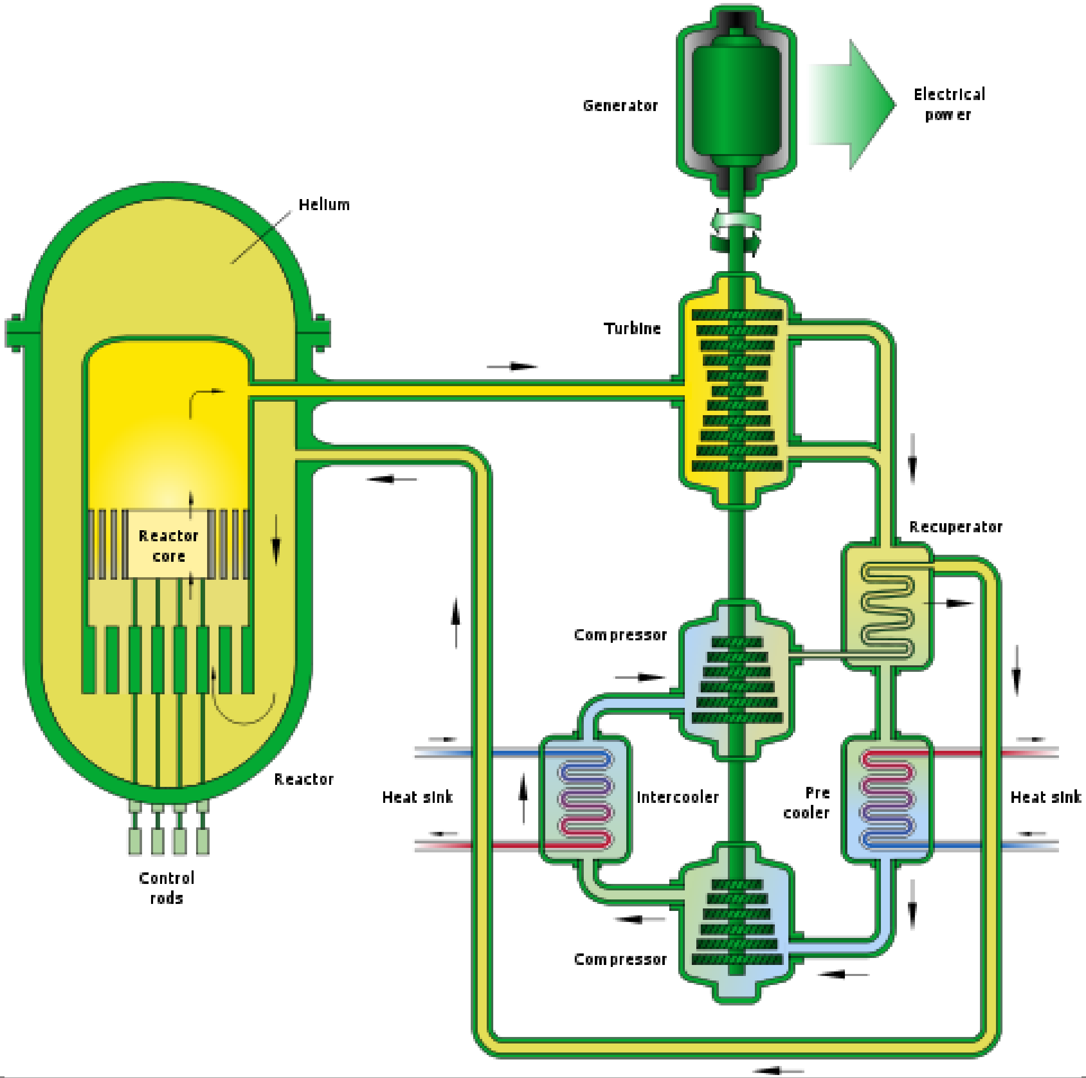
Generation IV: Thermal reactors

MSR: Molten Salt Reactor



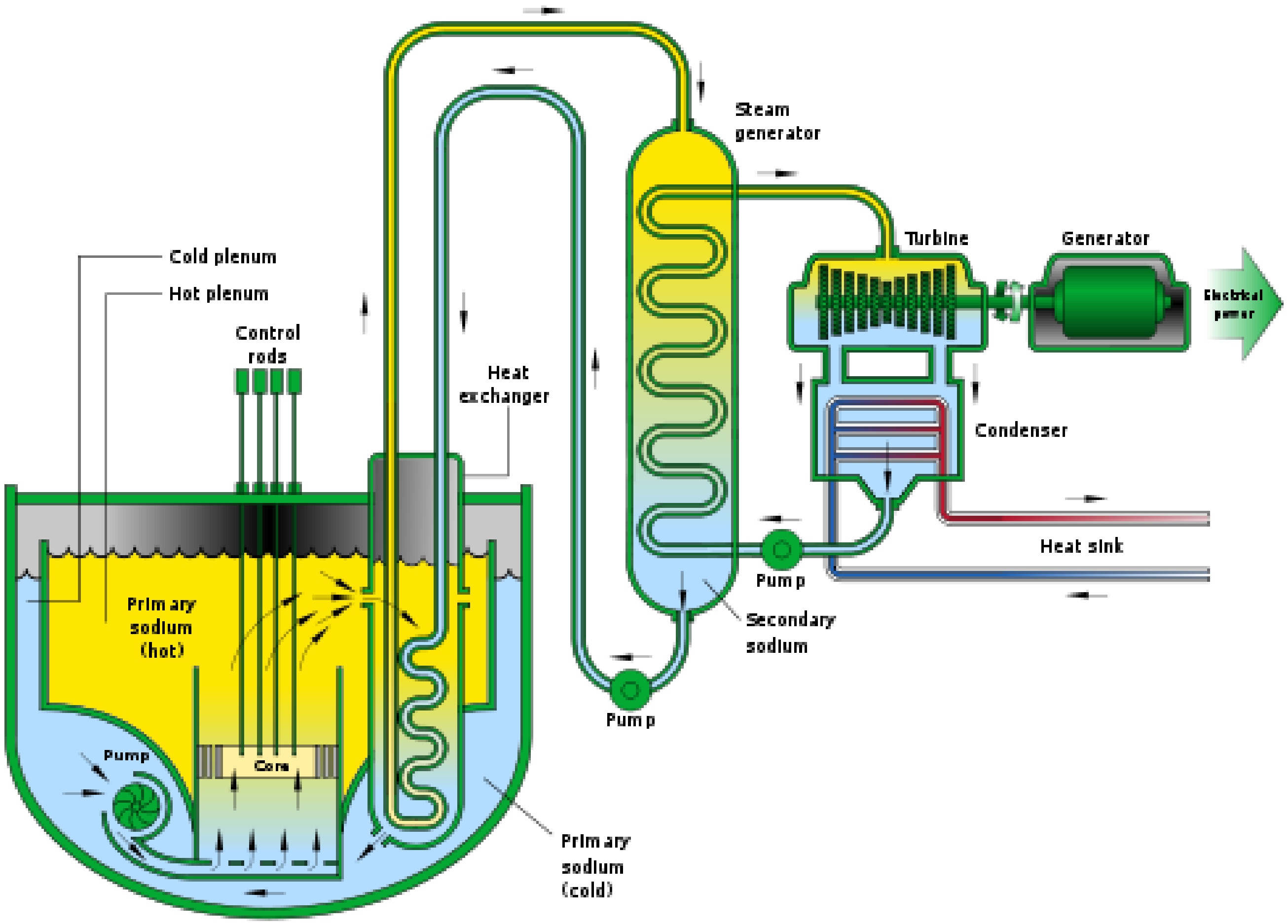
Generation IV: Fast reactors

GFR: Gas-Cooled Fast Reactor



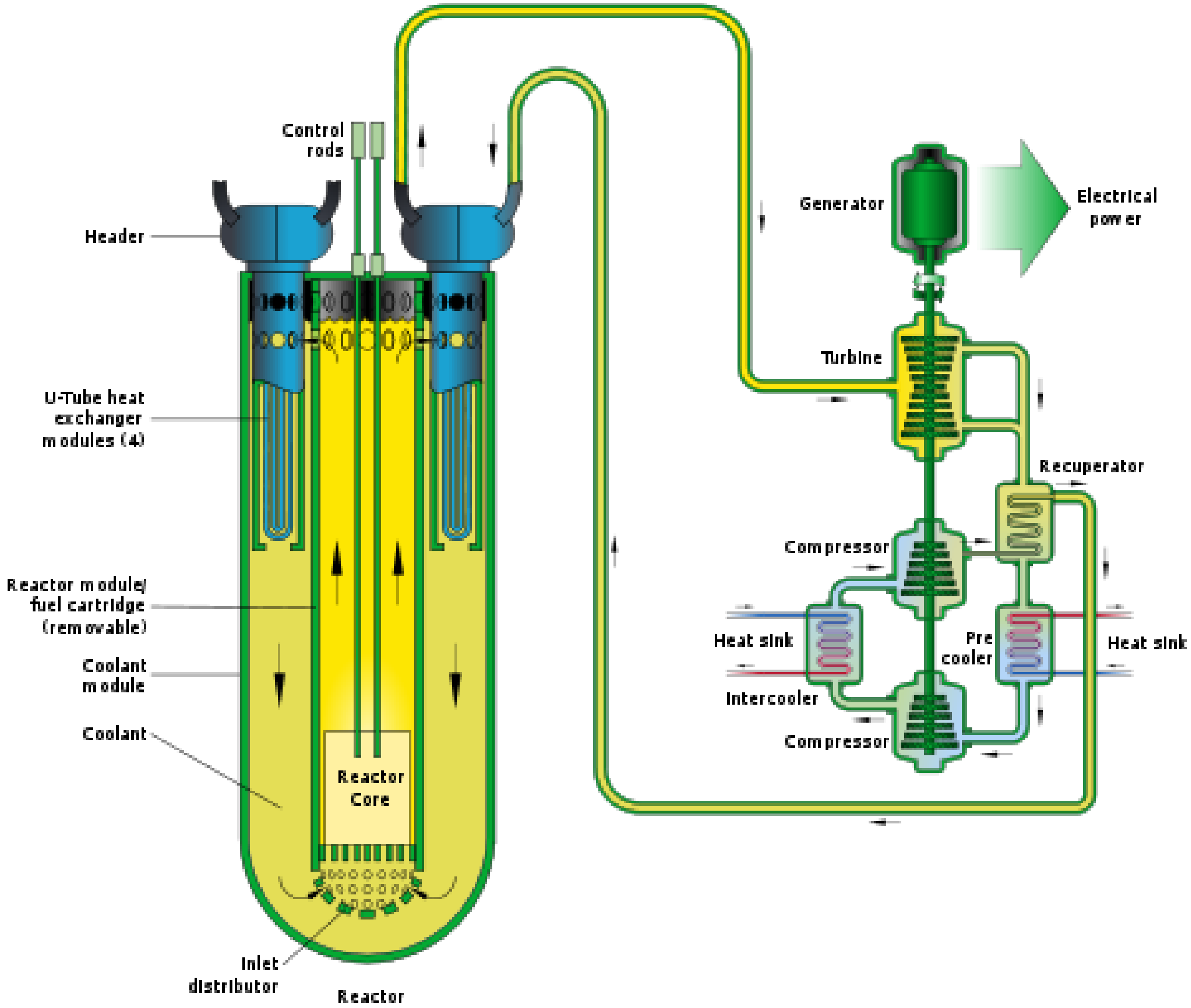
Generation IV: Fast reactors

SFR: Sodium-Cooled Fast Reactor



Generation IV: Fast reactors

LFR: Lead-Cooled Fast Reactor



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Gen IV: Pros & cons

+ Nuclear waste that lasts for decades instead of millenia

+ 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

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