GET1024 / GEC1036 Lecture 10

Nuclear Power (Principles & Types)

Introduction

- History, Current Situation, For & Against Nuclear

Some Basic Principles

- Energy Consideration, Chain Reaction, Moderation, Criticality, Generic PWR

Types of Reactors

- PWR, BWR, PHWR, LWGR, GCR, FBR

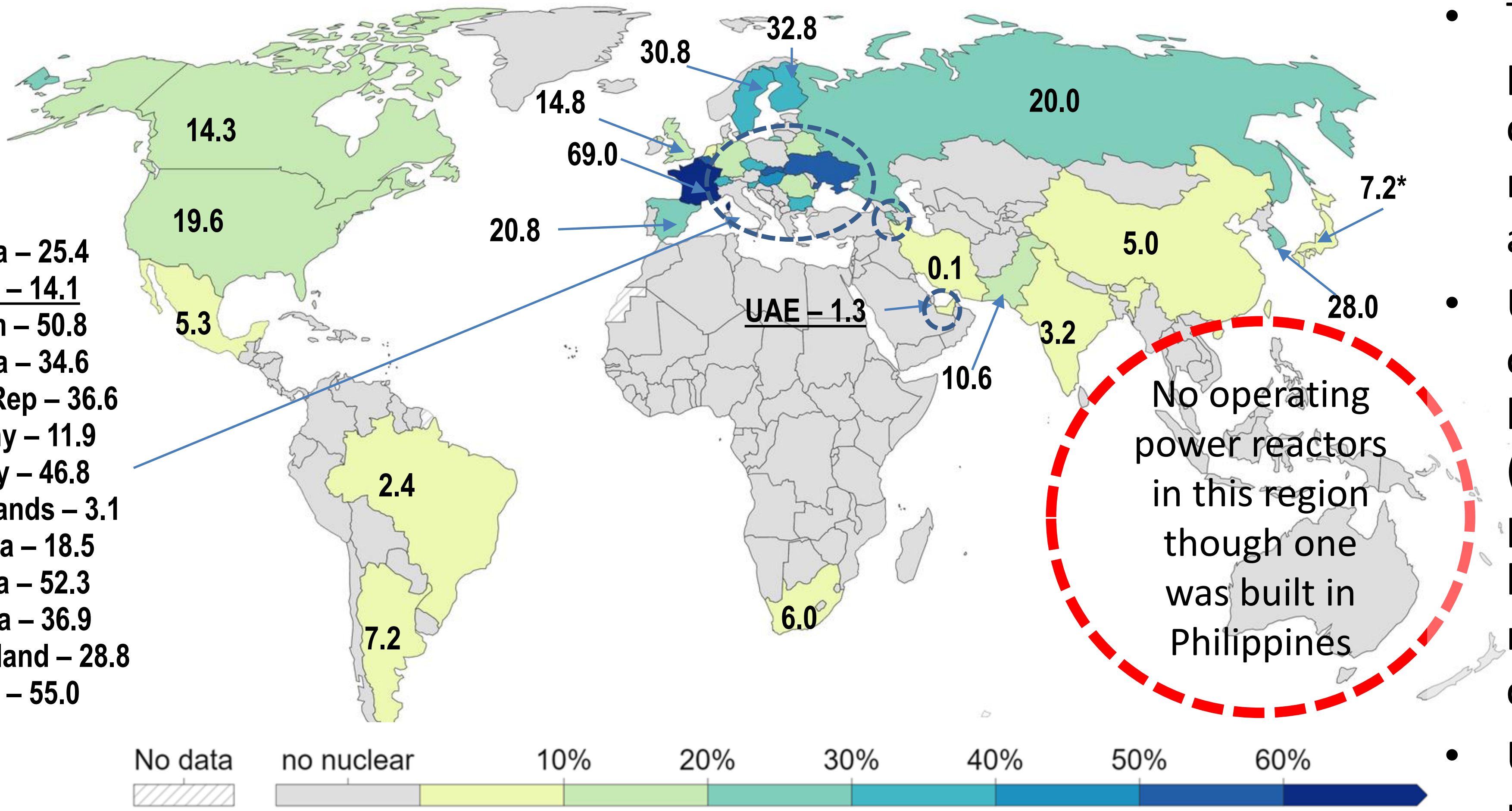
Current Situation in World

- **423 nuclear power reactors** currently in operation
- Generate around **378 754 MW** of electrical power
- Operating in **32 countries**
- **19,440** Reactor-Years of operation
- **~ 10%** of world total electricity production
- **56** more power reactors are **under construction**
- **~ 245 research reactors** in **55 countries**
- **~ 180 nuclear reactors** in **naval vessels**

https://www.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx

Percentage of Electricity Generated by Nuclear Reactors

Armenia – 25.4
<u>Belarus – 14.1</u>
Belgium – 50.8
Bulgaria – 34.6
Czech Rep – 36.6
Germany – 11.9
Hungary – 46.8
Netherlands – 3.1
Romania – 18.5
Slovakia – 52.3
Slovenia – 36.9
Switzerland – 28.8
Ukraine – 55.0



** In 2021, some of Japan's NPP are still suspended due to Fukushima accident. Before the accident, nuclear produced about contributed 30% with 33 reactors.*

- The map shows the percentage of electricity of countries generated by nuclear reactors. Numbers are in % for 2021.
- US has the highest number of reactors (94) and France has the largest percentage (69%) of electricity produced. China has the highest number of new reactors (16 since 2018) connected to grid
- UAE and Belarus started to produce electricity through nuclear. Bangladesh, Turkiye and Egypt have started construction.

https://en.wikipedia.org/wiki/Nuclear_power#/media/File:Nuclear-energy-electricity-production.png

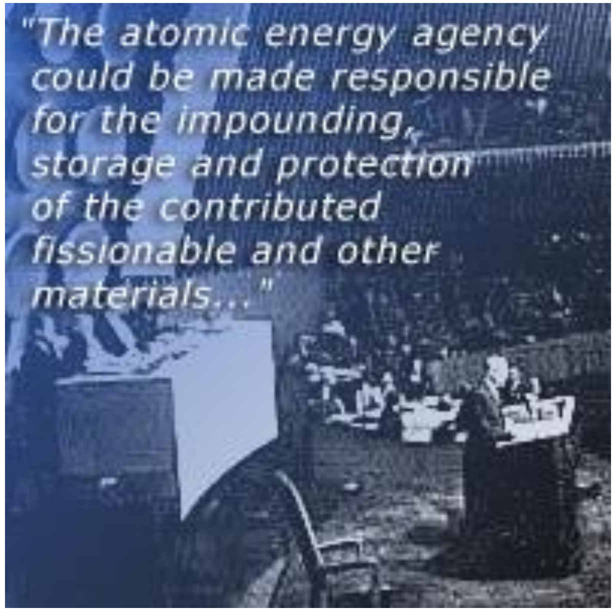
PRIS - Miscellaneous reports - Nuclear Share (iaea.org)

History of Nuclear Energy 1

- **1789** Martin Klaproth discovered uranium
- **1896** Curies isolated radium and polonium, coined the term "radioactivity"
- **1899** Rutherford distinguished α and β particles and discovered half-life
- **1909** Rutherford discovered that most mass is concentrated in a small nucleus
- **1920** Rutherford theorized a "neutron"
- **1932** Chadwick identified neutrons
- **1938** Hann & Strassman **split uranium** with neutron. Meitner & Frisch explained how and named it "fission".
- **1939** Fermi and Szilard measured **neutron multiplication**, concluded that chain reaction was possible.
- **1939** Einstein signed letter (with Szilard, Wigner, and Teller) warning Roosevelt of the possibility of nuclear weapon. US began nuclear bomb effort (though not vigorously).
- **1942** Fermi achieved **first nuclear chain reaction** at Chicago U. **Manhattan Project** with Oak Ridge (enriched uranium), Hanford (produced plutonium), Los Alamos (designed and assembled bomb)
- **1945** July – World first **nuclear weapon** test, the Trinity shot. Aug 6 & 9 – Atomic bombs, Little Boy at Hiroshima and Fat Man at Nagasaki
- **1951 EBR-1 reactor** (Experiment Breeder Reactor No 1) the **first to generate electricity**
- **1953** Eisenhower gave Atoms for Peace speech at UN, launched civilian programme

https://whatisnuclear.com/articles/nuclear_history.html

“Atoms for Peace”



Address by US President Dwight D. Eisenhower to the United Nations General Assembly, 8 December 1953

“The United States would seek more than the mere reduction or elimination of atomic materials for military purposes. It is not enough to take this weapon out of the hands of the soldiers. It must be put into the hands of those who will know how to strip its military casing and adapt it to the arts of peace.” [18:00 / 24:52]

“The United States knows that if the fearful trend of atomic military build-up can be reversed, this greatest of destructive forces can be developed into a great boon, for the benefit of all mankind. The United States knows that peaceful power from atomic energy is no dream of the future. The capability, already proved, is here today.” [18:23 / 24:52]

“The more important responsibility of this atomic energy agency would be to devise methods whereby this fissionable material would be allocated to serve the peaceful pursuits of mankind. Experts would be mobilized to apply atomic energy to the needs of agriculture, medicine and other peaceful activities. A special purpose would be to provide abundant electrical energy in the power-starved areas of the world.” [21:08 / 24:52]

“… the United States pledges … to devote its entire heart and mind to finding the way by which the miraculous inventiveness of man shall not be dedicated to his death, but consecrated to his life.” [24:03 /24:52]

https://www.iaea.org/about/history/atoms-for-peace-speech

History of Nuclear Energy 2

- **1954** USS Nautilus launched, first nuclear powered submarine. Obninsk reactor in USSR – first commercial NPP.
- **1957** Shippingport reactor in US (following submarine reactor design, PWR) began operation.
- **1960s – 70s** ~100 reactors built in US to produce about 20% of US electricity.
- **1960s** Anti nuclear movement (mainly against nuclear weapons) started. Grew in the 70s and also against nuclear energy.
- **1974** French PM Messmer launched huge nuclear power program in response to oil crisis ending up to supply 75% of France electricity.

- **1979** Three Mile Island reactor suffered partial meltdown. Radiation largely contained. "China Syndrome" movie released two weeks before accident.
- **1986** Chernobyl reactor suffered large power excursion releasing large amount of radiation. 50+ firefighters & operators died, up to 4000 civilians estimated to die of early cancer
- **2011** Four reactors at Fukushima Daiichi lost backup generators due to tsunami and suffer core melt down, hydrogen explosions. Radiation estimated 10 – 30% of Chernobyl. Zero death from radiation but large area of land evacuated.

https://whatisnuclear.com/articles/nuclear_history.html

Support for Nuclear Energy

- **Low greenhouse emission** over the whole process of energy production.
- **Powerful and efficient**. Capable of producing up to 1600 MW of electricity per reactor and often up to 6 reactors are built in one location. A 1000 MW reactor can supply enough electricity to an industrialized city of population ~ 500,000.
- **Low fuel cost**. Uranium is only a small part of the cost of running. Even if price of uranium goes up, the price of electricity will not change by much.
- **Easy Transportation**. 1 kg of enriched uranium produces as much energy as 100 tons of coal. Up 100 kg of enriched uranium or 10,000 tons of coal to produce 1000 MW of electricity for 24 hours. (Caution to students: watch out different numbers when comparing with U-235 alone, enriched U, natural ore from ground.)
- **Secure electricity source.** Can be depended on as a reliable part of electricity mix. It is not subject to changing weather or climate conditions, unpredictable fuel cost fluctuations or over-dependence on foreign suppliers.
- **Longer lasting supply** of uranium will last much longer compared to oil or natural gas using current technology and much longer if used in fast reactors or almost indefinitely if extracted from seas. Thorium could be an alternative source too.
- **Small quantity of waste** (But ... see disadvantage)

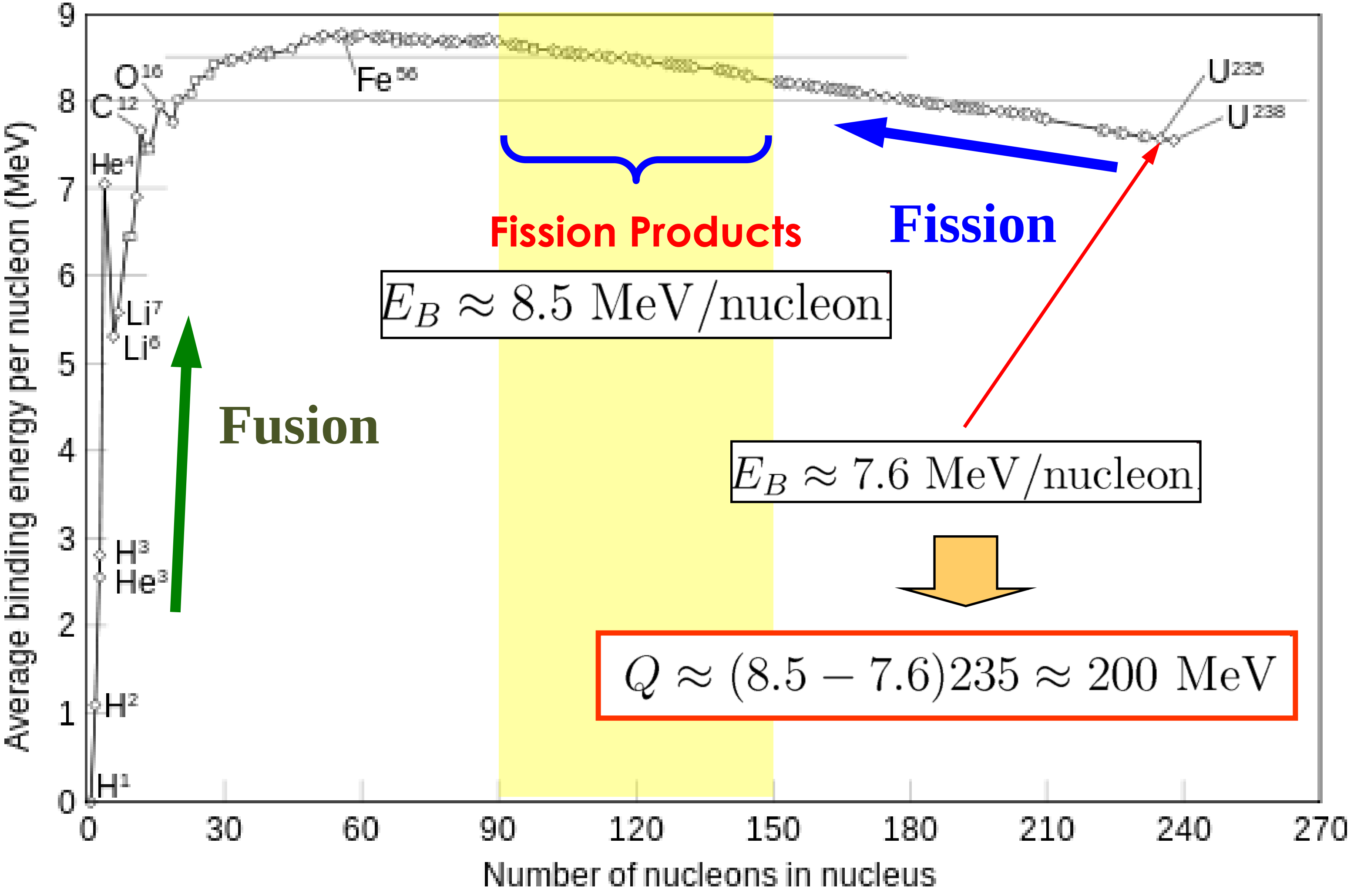
http://www.conserve-energy-future.com/advantages_nuclearenergy.php

Arguments against Nuclear Power

- **Safety** is always a public concern especially after Chernobyl and Fukushima. While much have been done to improve safety, the public perception is that power generation by nuclear means is a dangerous operation. (Will look at this in greater detail in next lecture.)
- Any **nuclear accident** may result in evacuation of a population up to 20 km radius and the area may remain unliveable for a very long time. Plutonium-239 which may contaminate the land has half-life of 24,000 years.
- **Nuclear wastes** can be a problem to deal with. There are both long, intermediate and short half life wastes which make it challenging to dispose/store them. While the quantity is small, they are a lot more "dangerous".
- **Building cost** of a nuclear power plant is higher than the others though the actual cost of running it for 40 – 60 years is likely to be lower than other plants producing the same amount of energy.
- **Decommissioning** of an NPP is also very expensive.
- There is concern that it may lead to **nuclear proliferation** (spread of nuclear weapons).
- The reactor is a **potential target for terrorists** and spent fuel rods may be misused by those with ill-intent.

Nuclear Fission and Nuclear Fusion (from Binding Energy Curve)

- Possible to get energy from **nuclear fission** (splitting of heavy nucleus into two almost equal mass pieces) and **nuclear fusion** (fusing two light nuclei into a heavier nucleus) due to difference in binding energy.



<u>Comparing chemical energy obtained from fossil fuels:</u>

- 1 ton of coal may release up to 3×10^{10} J.
- 1 ton of 100% U-235 would produce 8×10^{16} J

$$\boxed{\frac{1000}{0.235} 6.0 \times 10^{23} \times (200 \times 1.6 \times 10^{-13})}$$

- 1 ton of 4% enriched U would produce about 3×10^{15} J (~100,000 times more energy per unit mass of fossil fuel!)

https://en.wikipedia.org/wiki/Nuclear_binding_energy

Basic Principles (Energy)

- The ~ 200 MeV of energy per fission is approximately distributed as follows:

Produced from fertile Th-232

Produced from fertile U-238

Component	Energy (MeV) per fission event		
	U-233	U-235	Pu-239
Fission fragments’ kinetic energy	168.2	169.1	175.8
Prompt neutrons’ kinetic energy	4.9	4.8	5.9
Prompt gamma rays	7.7	7.0	7.8
Decay gamma rays	5.0	6.3	5.2
Decay beta particles	5.2	6.5	5.3
Decay neutrinos	6.9	8.8	7.1
Total	**197.9**	**202.5**	**207.1**

Immediately released

released during subsequent β– decays

Not absorbed by system

- **Fissile** material is material that is capable of undergoing fission reaction after absorbing thermal neutron, e.g., U-233, U235 & Pu-239. Note: U-235 is the only naturally occurring fissile materials (present in sufficient quantity on Earth).
- **Fertile** material is material that can be converted to fissile material by neutron transmutation and subsequent nuclear decays, e.g., Th-232 & U-238.

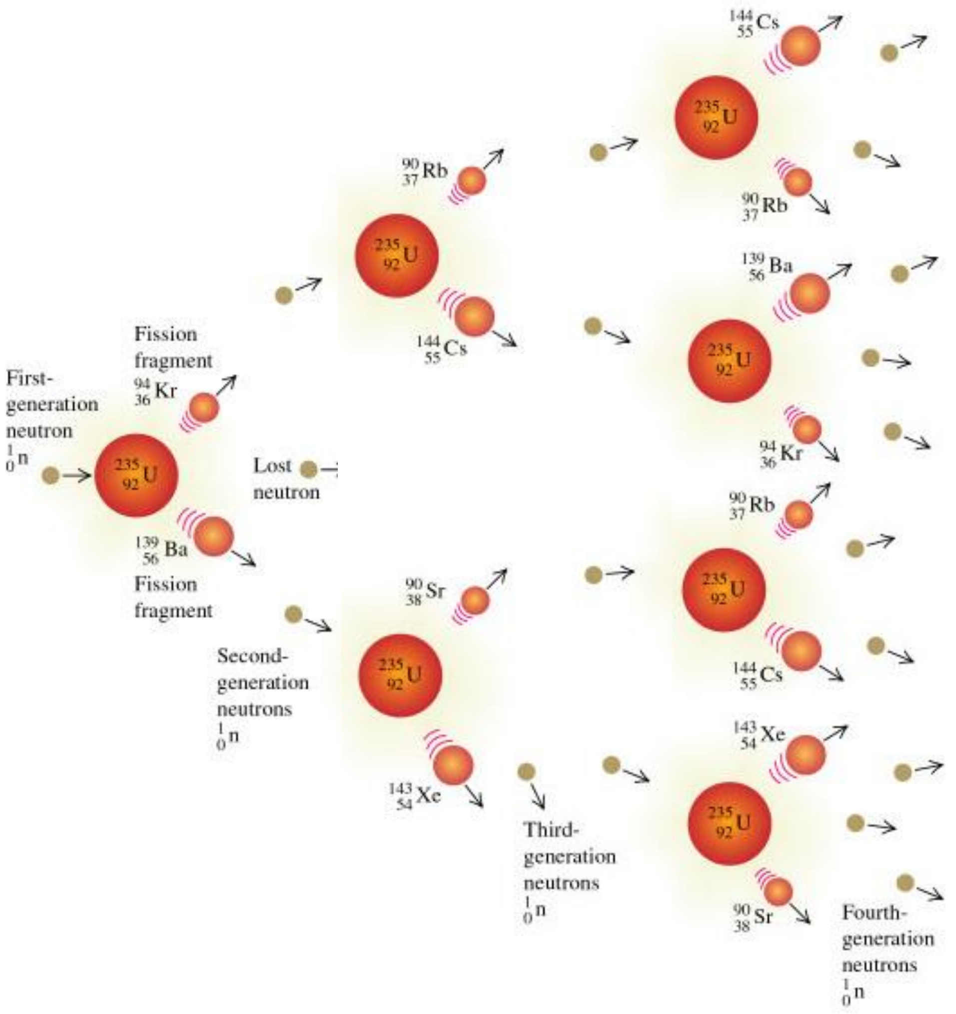
Chain Reaction

- Most fission process also produces 2 – 3 fast neutrons, e.g.,

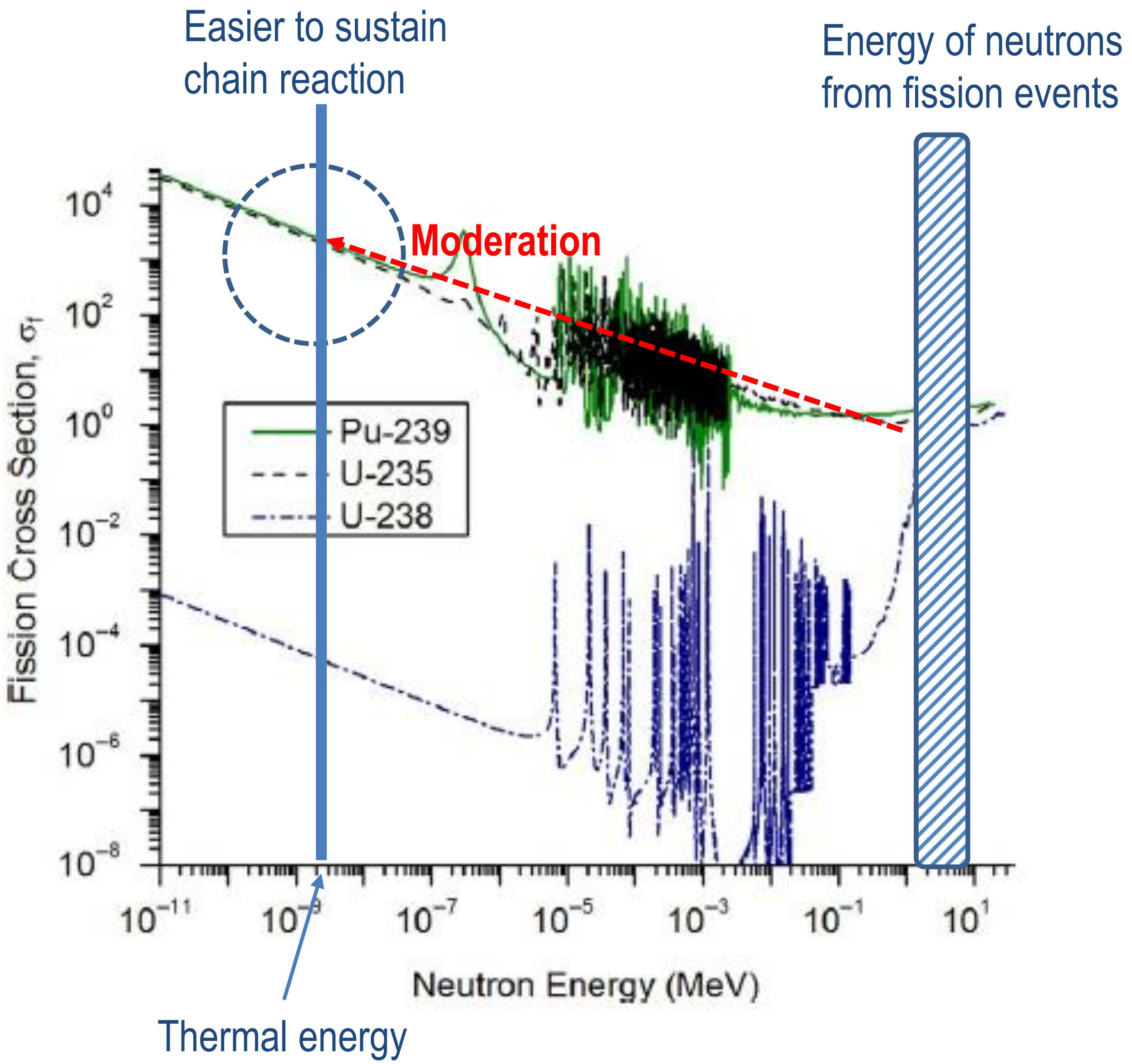
$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U}^{*} \longrightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$$

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U}^{*} \longrightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + 2\,{}^{1}_{0}\mathrm{n}$$

- The neutrons produced from fission could cause further fission of other nuclei if not lost.
- Possibility of a **chain reaction** – either fast and growing exponentially (atomic bomb) or in a controlled manner where it proceeds slowly.
- A **critical mass / assembly** (minimum mass such that the number of fission in each generation does not decrease) must be present before the chain reaction can occur.



Fission cross-section at different energies



Holbert and Murray, Nuclear Energy, pg 91

- The graphs on the left show the fission cross-section for U-235, U-238 and Pu-239 for different energy of neutrons.

  Note: Cross-section is a technical concept. Important just to remember that it is proportional to the probability of the event – in this case – the probability of fission.

- The chance for fission is much lower for U-238 compared to both U-235 and Pu-239.
- For U-235 & Pu-239, the chance of fission is much higher when neutron energy is low.
- Most reactors use thermal (room temperature ~ 0.025 eV) neutrons to sustain chain reaction.

Implication: Need to slow down (**moderate**) neutrons from previous fission process.

Choice of Moderator

- Neutrons need to be slowed down from about 2 MeV (20,000 km/s) to around 0.025 eV (2 km/s). What are the best materials to do so?
- The most effective particle to slow down the neutrons should have mass very similar to that of neutrons. The ideal particle is the proton or hydrogen nucleus. It takes about 26 collisions to do so. Uses hydrogen in water molecules rather than hydrogen gas.
- But hydrogen (H-1) may also capture the neutron to form deuterium (H-2). This neutron will then be lost and not contribute to fission process! Need to have more U-235 atoms to reach critical conditions, i.e., need to enrich the natural uranium.

Moderator	**Thermal Cross Section (10^{-24} cm^2)**		**Fast Cross Section (10^{-24} cm^2)**		**Number of Scattering to reach thermal energy from 2 MeV**
	Scattering	Capture	Scattering	Capture	
H-1	20	0.2	4	0.00004	26

http://www.radioactivity.eu.com/site/pages/Neutrons_Moderators.htm
https://en.wikipedia.org/wiki/Neutron_cross_section

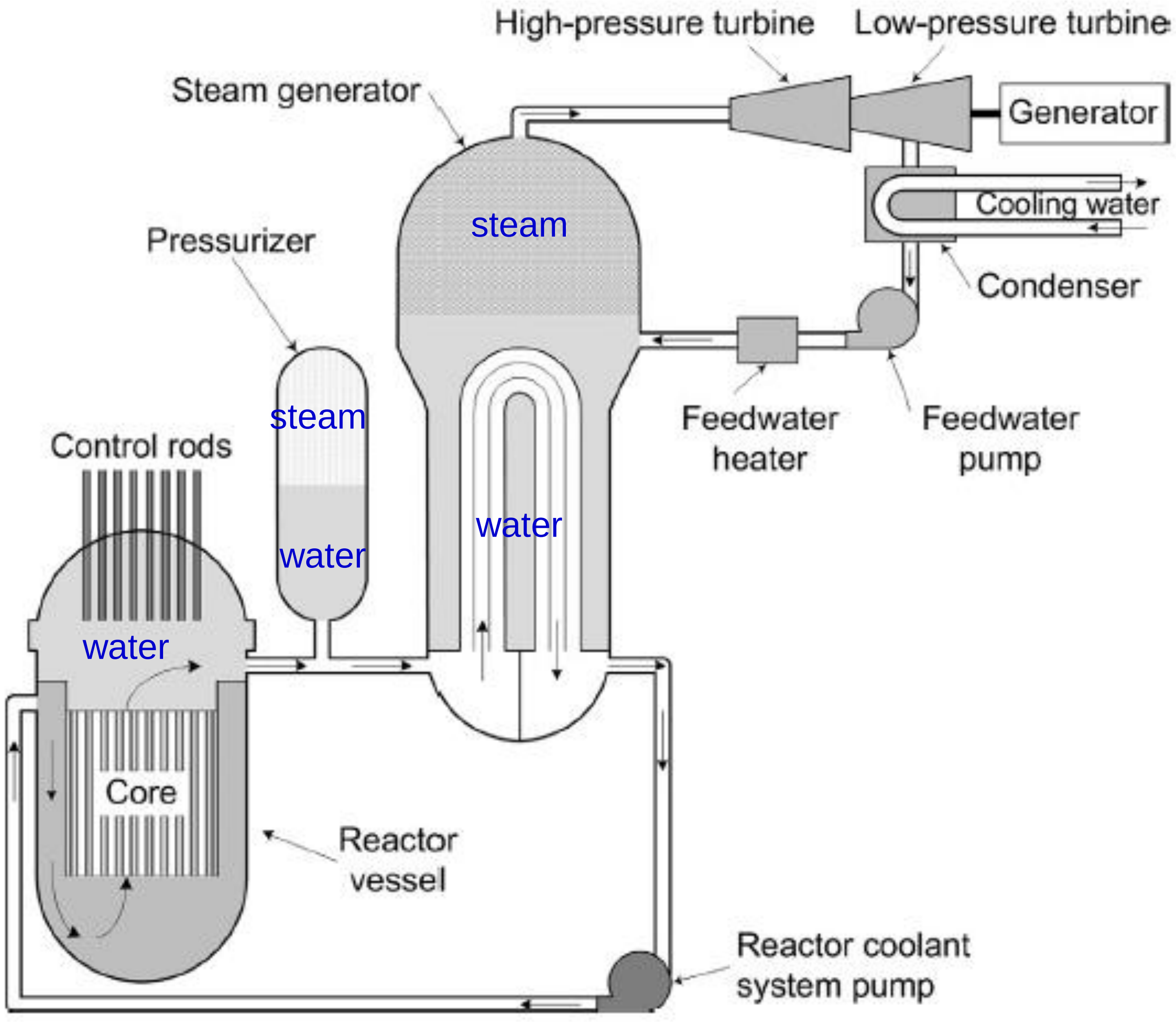
Choice of Moderator

- May also use deuterium ($^2_1\mathrm{H}$). It takes more collisions (31 instead of 26) to slow down to thermal energies, but the chance of capture vs scattering is much lower (less than 0.01% cf 0.1% for normal hydrogen at thermal energies).
- Using heavy water, i.e., water molecules with hydrogen (H-1) replaced by deuterium (H-2), the fuel needs not be enriched to achieve critical conditions as will be seen in the CANDU reactors.
- Carbon is also a possible choice and is used in some reactors. The number of collisions needed to slow down the neutrons is substantially higher (120), but the capture vs scattering probability is low enough for the reactor to go critical (with or without enrichment)

Moderator	Thermal Cross Section (10^{-24} cm^2)		Fast Cross Section (10^{-24} cm^2)		Number of Scattering to reach thermal energy from 2 MeV
	Scattering	Capture	Scattering	Capture	
H-1	20	0.2	4	0.00004	26
H-2	4	0.0003	3	0.000007	31
C-12	5	0.002	2	0.00001	120

http://www.radioactivity.eu.com/site/pages/Neutrons_Moderators.htm
https://en.wikipedia.org/wiki/Neutron_cross_section

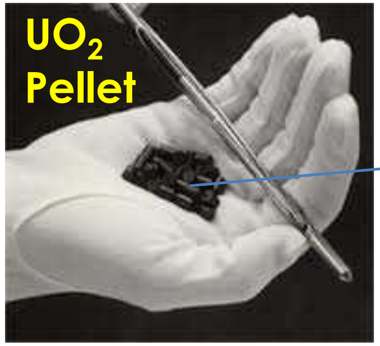
A Generic Pressurized Water Reactor

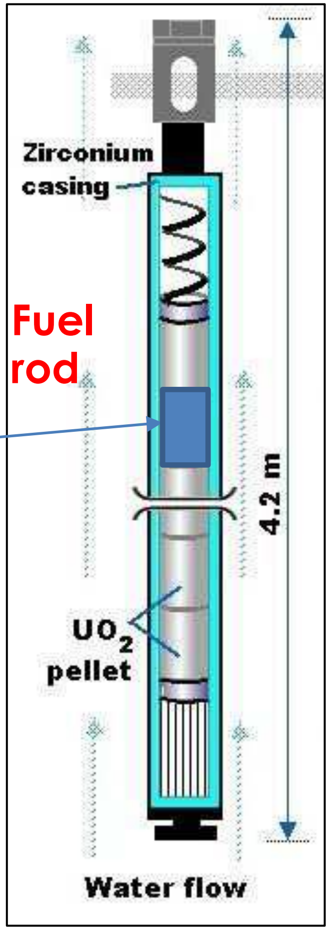


Holbert and Murray, Nuclear Energy, pg 301

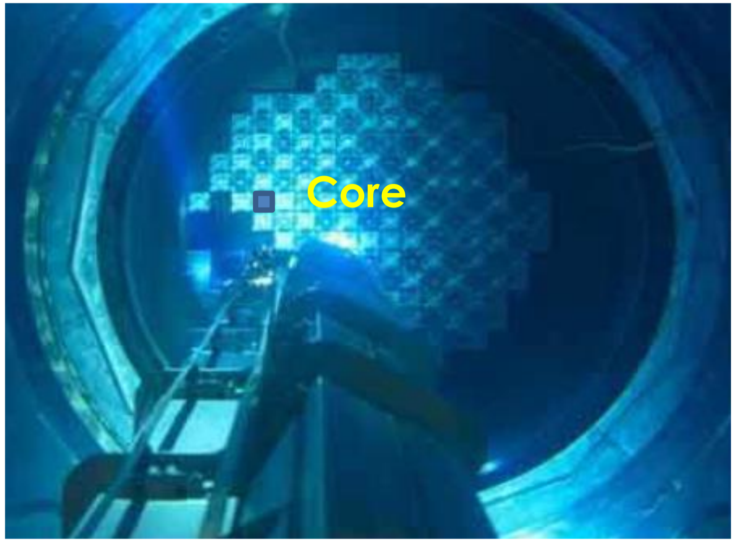
- **Reactor Vessel**: Heart of plant – fission takes place. Heat carried away by coolant (normal water). **Control rods** controls the rate of energy production of the reactor and used in emergency SCRAM.
- **Pressurizer**: maintains pressure in reactor vessel. Action of heater (increases temp and pressure) and spray (condenses steam and reduces pressure).
- **Steam Generator**: thin-walled tubes for heat exchange between primary and secondary circuits. Steam is collected to drive the turbine to produce electricity.
- Water to cool the **condenser** dumps heat to the cooling tower or sea / lake.
- Many other **safety and control systems** are not shown.

Inside the Reactor Vessel of PWR





200 – 300 fuel rods per fuel assembly
e.g. (17 x 17)

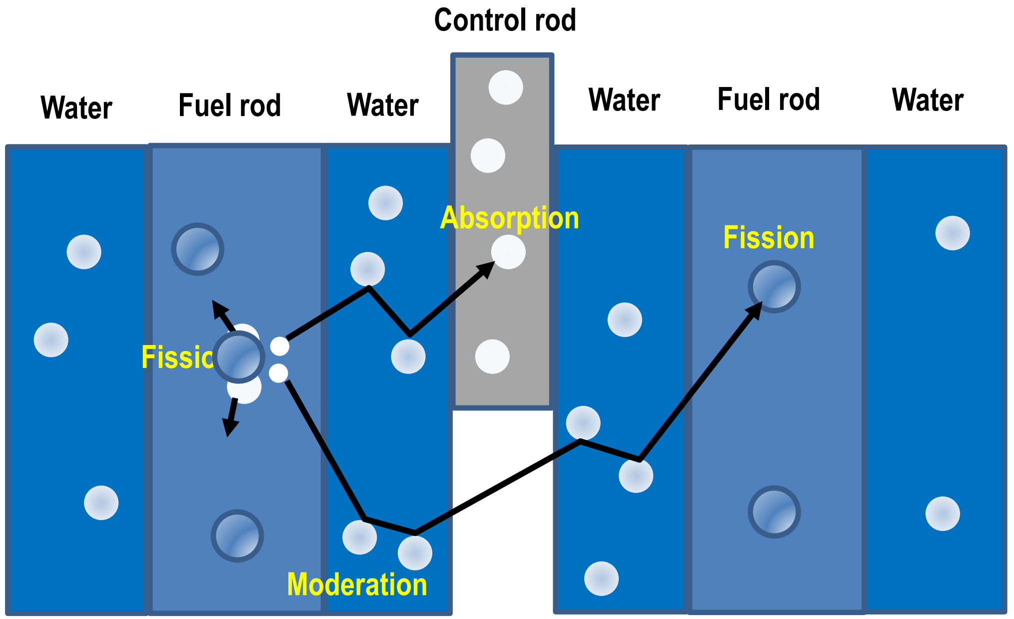


150 to 250 fuel assembly in reactor core (80 – 100 tonnes of uranium).

Absorbing Neutrons

- We also need materials that can absorb the neutrons
  - To control to keep exact critical condition (boric acid and control rods)
  - To shut down the reactor in an emergency (control rods)
- Control rods may be made of boron carbide (B_4C) or silver-Indium-cadmium (Ag-In-Cd) alloy. These materials have **high absorption cross-section**.

Absorber	Thermal Cross Section (10^{-24} cm^2)	
	Scattering	Absorption
B-10	2	200
Cd-113	100	30,000
In-115	2	100

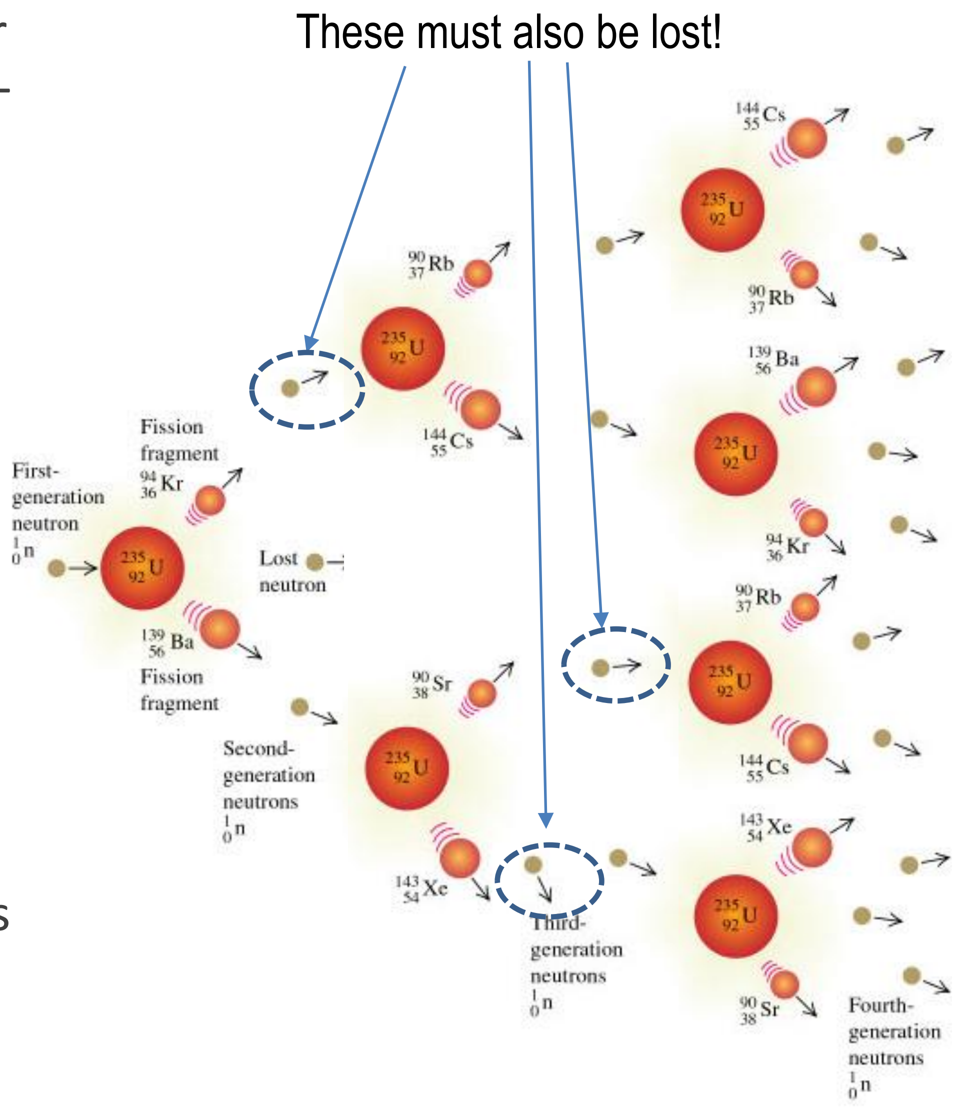


Controlling the Rate of Fission

- For energy production, “gain” in the number of neutrons for each generation – effective neutron multiplication factor *k* – must be kept to unity (after reaching power needed).
- The number of neutrons in a reactor can be reduced by introducing higher level of neutron absorbers by

  (1) higher boric acid concentration in coolant

  (2) lowering the control rods into fuel assemblies.
- Boric acid provides a slower response (to take care of fuel depletion between refueling and at start up) while control rods acts faster (during operations – different load requirements and emergency).
- The duration of each generation is very short, about 10^{-5} s. Neutrons during the fission process (known as **prompt neutrons**) are produced in 10^{-14} s! How can the control rods be manipulated in time to ensure the exact conditions are met (k_{eff} = 1)?



Delayed Neutrons

- **Prompt neutrons** (produced immediately in the fission process) are not the only neutrons produced in a reactor.
- **Delayed neutrons** are emitted by **neutron rich fission products** that are called the delayed neutron precursors. These precursors usually undergo beta decay, e.g.,

Fission Product $\boxed{{}^{140}_{54}\mathrm{Xe}} \xrightarrow{\beta^-} {}^{140}_{55}\mathrm{Cs} \xrightarrow{\beta^-} {}^{140}_{56}\mathrm{Ba} \xrightarrow{\beta^-} {}^{140}_{57}\mathrm{La} \xrightarrow{\beta^-} \boxed{{}^{140}_{58}\mathrm{Ce}}$ **stable**

- However, a small fraction of them are excited enough to undergo **neutron emission** instead of β-decay.
- The emission of neutron happens orders of magnitude (from milliseconds to about 1 minute) later compared to the emission of the prompt neutrons. They contributed to less than 1% of all the neutrons produced but their timescale of seconds played a very important role in ensuring stable operation of the reactor. The addition of delayed neutrons changes the effective time for each generation from ~10^{-5} s to ~ 0.1 s.
- Delayed neutrons allow to operate a reactor in a prompt subcritical, delayed critical condition.

http://www.nuclear-power.net/nuclear-power/fission/delayed-neutrons/

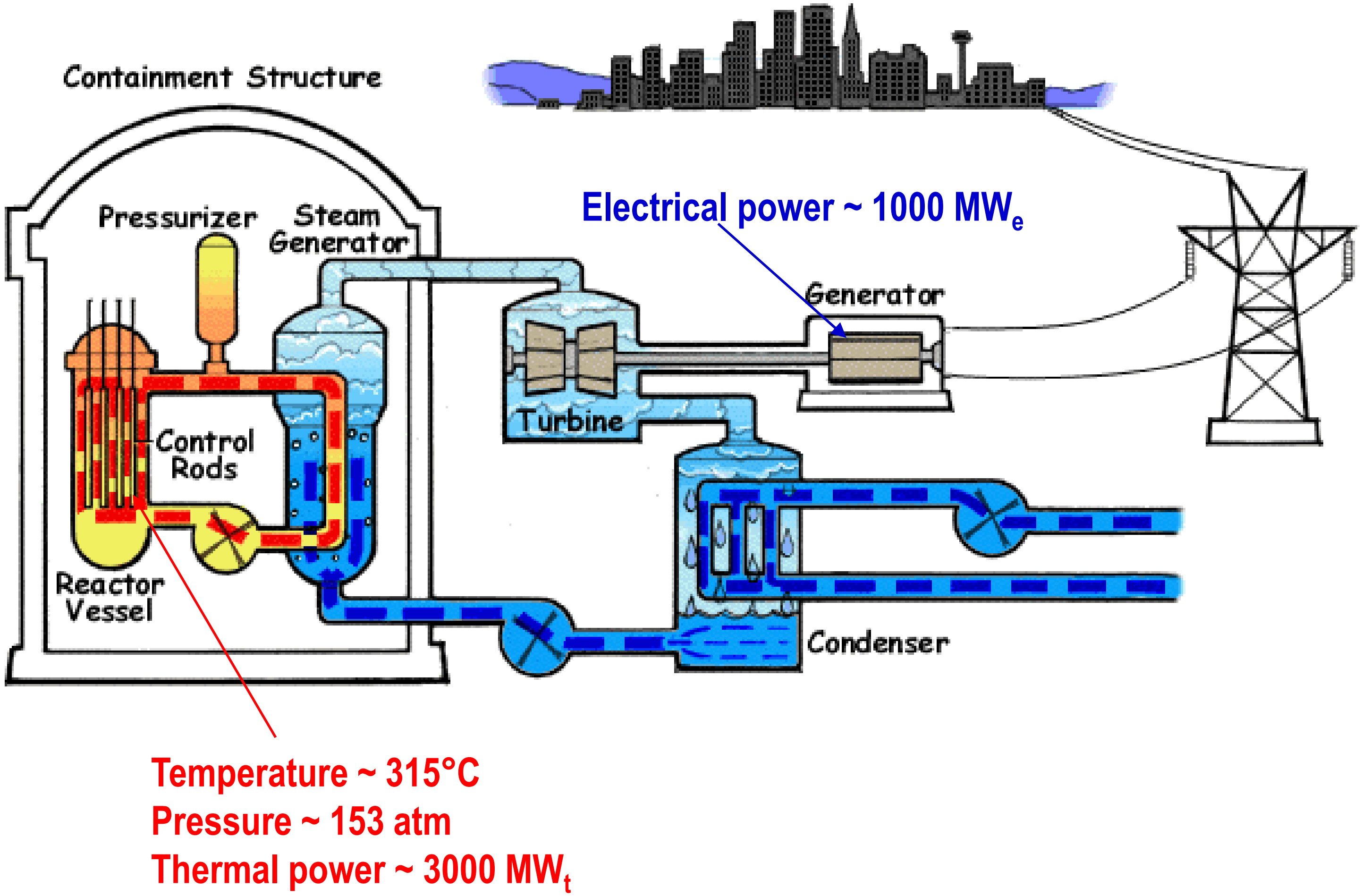
Types of Nuclear Power Reactors (from IAEA PRIS, 6 Jan 2023)

Reactor Type	Reactor Type Descriptive Name	Coolant	Moderator	Operating Reactors*		Under Construction	
				Number	Electrical Capacity [MWe]	Number	Electrical Capacity [MWe]
PWR	Pressurized Light-Water-Moderated and Cooled Reactor	Water	Water	303	290,717	49	52,903
BWR	Boiling Light-Water-Cooled and Moderated Reactor	Water	Water	49	49,565	2	2,653
PHWR	Pressurized Heavy-Water-Moderated and Cooled Reactor	Heavy Water	Heavy Water	47	24,314	3	1,890
LWGR	Light-Water-Cooled, Graphite-Moderated Reactor	Water	Graphite	11	7,433	-	-
GCR	Gas-Cooled, Graphite-Moderated Reactor	Carbon Dioxide	Graphite	8	4,685	-	-
FBR	Fast Breeder Reactor	Sodium	None	3	1,400	3	1,412
HTGR	High Temperature Gas Cooled Reactor	Helium	Graphite	1	200	-	-
Total				**422**	**378,314**	**57**	**58,858**

** Excludes 16 suspended reactors in Japan*

https://www.iaea.org/PRIS/WorldStatistics/OperationalReactorsByType.aspx

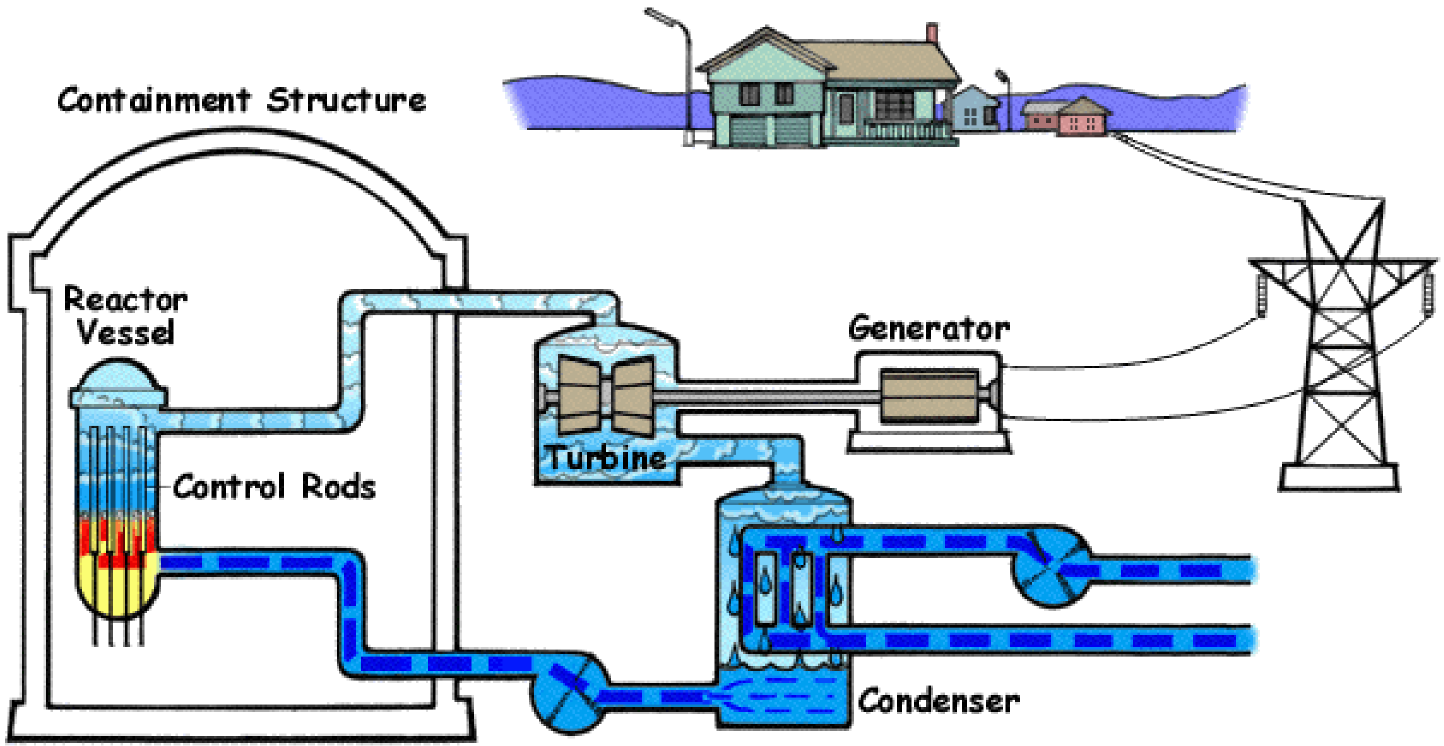
PWR (Pressurized Water Reactor)



- Moderator and Coolant – Both normal (also call light) water.
- Fuel – Enriched Uranium (~ 4%)
- Operate under very high pressure (~ 150 atm) that water remains in liquid state in primary circuit at high temperature (~320°C).
- Produces up to 1750 MW$_e$ (electric)
- Steam is generated in secondary circuit to drive the turbines.
- Most commonly operated power reactors. Found in many countries, e.g., US, France, China, Russia (known as VVER), Japan, Korea, etc.
- Most reactors under construction are PWRs

https://en.wikipedia.org/wiki/Pressurized_water_reactor

BWR (Boiling Water Reactor)

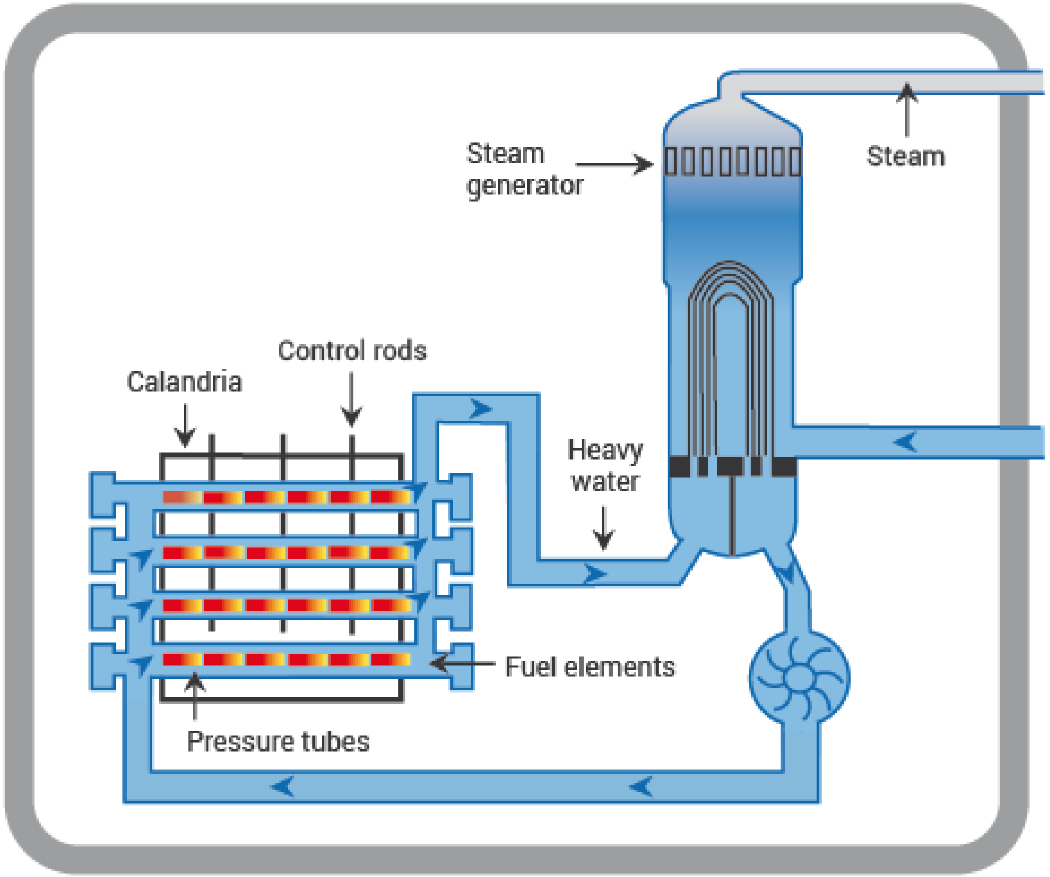


- Moderator and Coolant – Normal Water
- Fuel – Enriched Uranium (~ 4%)
- Produces up to 1500 MWe
- Under high pressure (~70 atm) but at lower pressure than PWR.
- Steam is generated directed in reactor vessel.
- Control rods from bottom.
- Found in US, Japan (including Fukushima-Daiichi), Sweden, Finland, Mexico, Spain, Switzerland and India.

https://www.nrc.gov/reading-rm/basic-ref/students/animated-bwr.html

PHWR (Pressurized Heavy Water Reactor)

A Pressurized Heavy Water Reactor (PHWR/Candu)

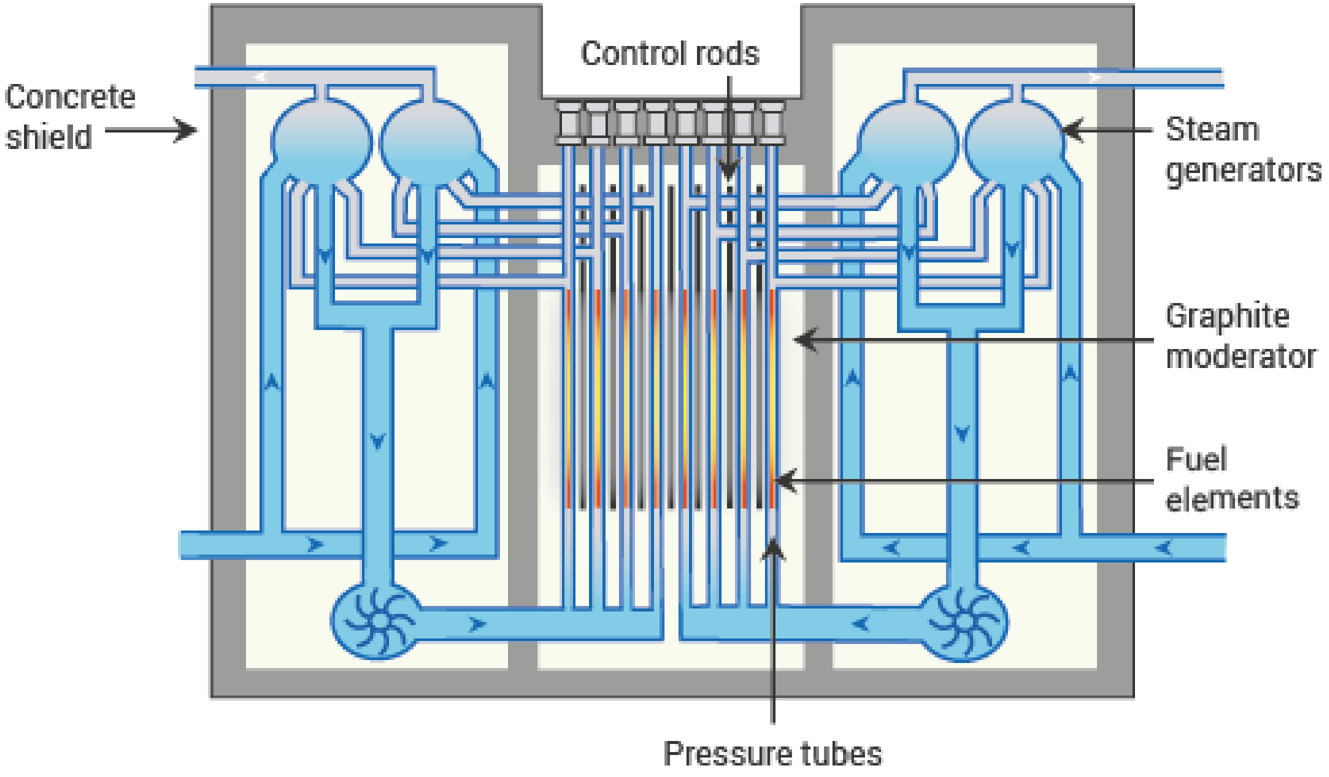


- Also known as CANDU – Canada Deuterium Uranium.
- Moderator – Heavy Water (Deuterium)
- Fuel – Natural Uranium (0.71% U-235)
- Produces up to ~850 MWe
- Most efficient in uranium utilization (higher power per unit of U mined).
- Can also used other fuel including depleted uranium or thorium.
- Similar to PWR that steam is generated in secondary circuit.
- Calandria: Contain fuel and moderator. Control rods right angle to pressure tubes.
- Can be refuelled without stopping operation.
- Used mainly in Canada (19) and India (18). All operating reactors in Argentina (3) and Romania (2) are also PHWRs.

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx

LWGR (Light Water Graphite Moderator Reactor)

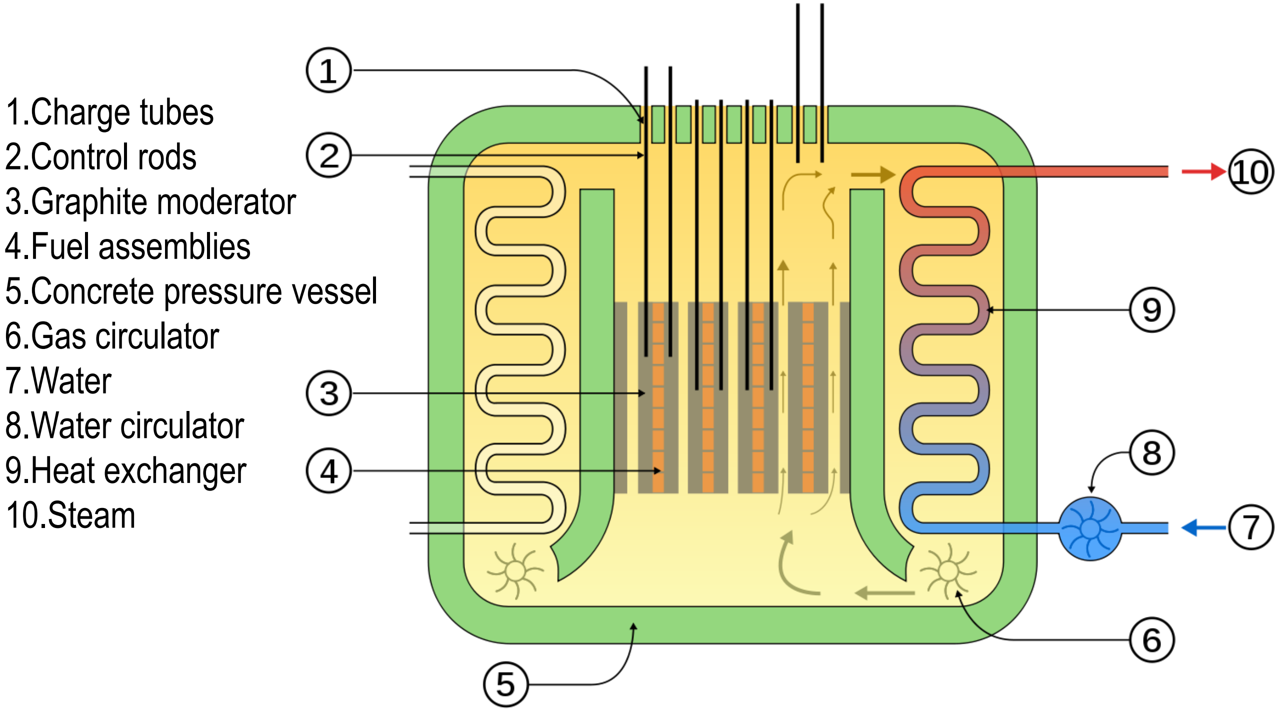
A Light Water Graphite-moderated Reactor (LWGR/RBMK)



- Fuel: Slightly enriched uranium
- Coolant: Light water.
- Moderator: Graphite
- No secure containment compared to Western designs. Serious accident in Chernobyl in 1986.
- Design disadvantage: positive feedback with water in pressure tube is lost or boiled. *(Compared to PWR which is water-moderated. Loss of water in PWR stops the reaction as neutrons are not moderated.)*
- Safety features and design improved after Chernobyl.
- RBMKs built in former Soviet Union and East Europe. Now only 11 RBMKs of ~ 1000 MWe remain in operation in Russia.

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/appendices/rbmk-reactors.aspx

GCR (Gas-cooled Reactor)

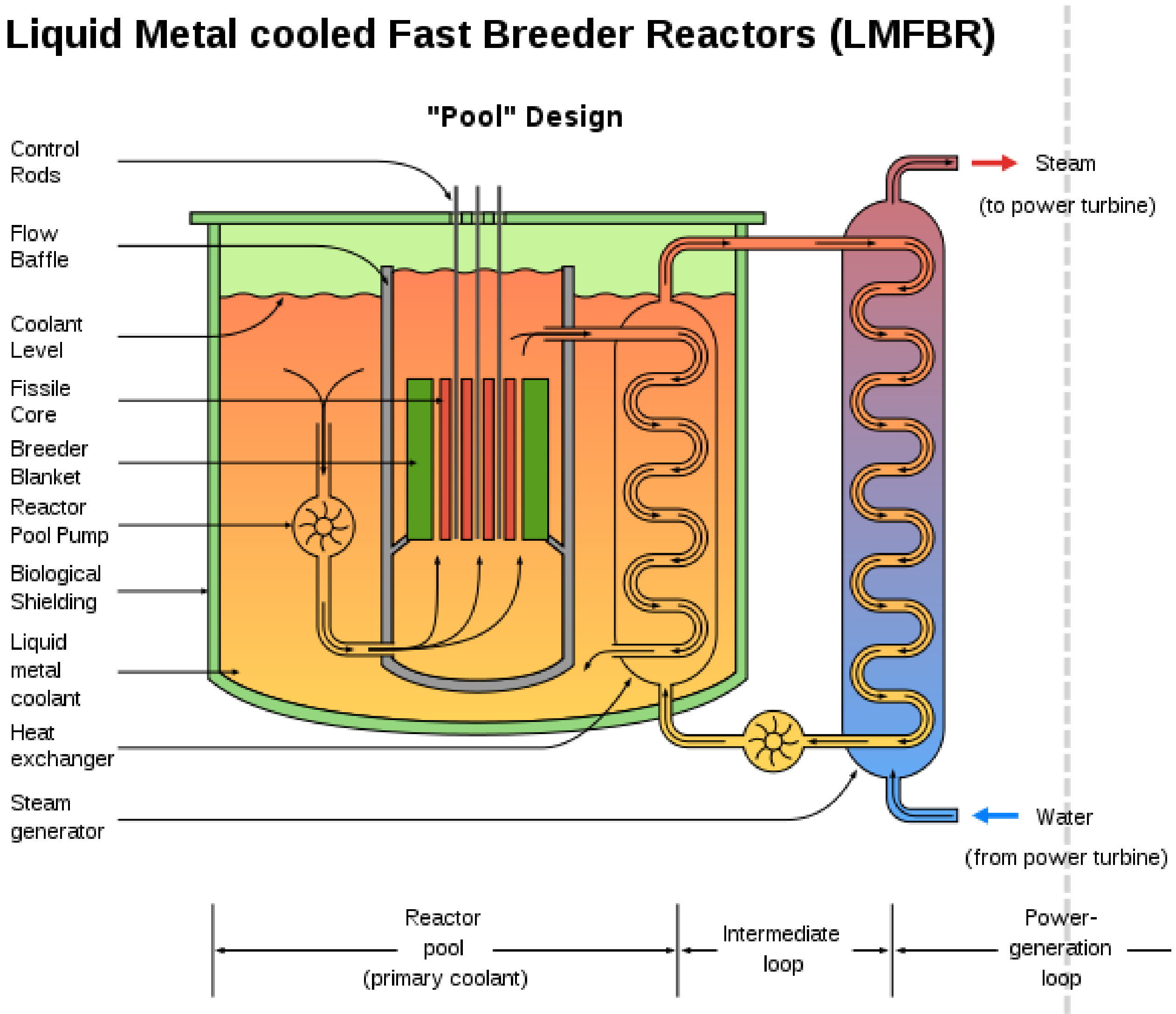


AGR – Advanced Gas-cooled Reactor

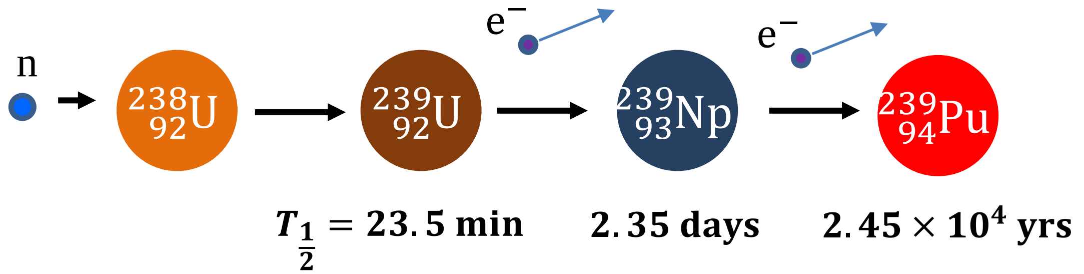
- Fuel: 2 – 3% Enriched (AGR) or natural Uranium (Magnox)
- Coolant: Gaseous CO_2
- Moderator: Graphite
- Advantage: coolant can be heated to higher temperature (640°C in AGR) resulting in higher efficient for power production.
- Disadvantage: low power density which requires large size of the reactor for relatively smaller power requirements.
- Power production may be direct (gas drive the turbines) or indirect (gas boils water in secondary circuit, steam drives turbine)
- Currently operating only in UK (8 AGR – Advanced Gas-cooled Reactor of ~600 MWe which replaced the original GCR Magnox).

https://en.wikipedia.org/wiki/Advanced_gas-cooled_reactor

FBR (Fast Breeder Reactors)



- Use fast neutron directly – no moderation.
- Smaller fission cross-section – needs even higher enriched uranium (usually 20% or more)
- Coolant – cannot be water (moderator). Usually sodium – liquid over large range of temperature (97.8 – 883°C) .
- But sodium reacts strongly with water and oxygen!
- Blanket of U-238. Absorbs neutron. Breed plutonium at both core and blanket:



- Produce more fissile materials than used!
- Plutonium can be removed by reprocessing and used in reactor (as mixed oxide MOX fuel).
- Currently, 2 in Russia and 1 in China.

https://en.wikipedia.org/wiki/Breeder_reactor