Nuclear Reactor Physics

Nuclear reactors and nuclear power

Jan Dufek

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KTH Royal Institute of Technology

The fission chain reaction

What is the physical meaning of the multiplication factor k?

The multiplication factor can be interpreted in various ways, e.g. as

- the ratio of rates at which neutrons are being produced and destroyed (by absorption and leakage).
- the ratio of the number of fission neutrons in one generation and the number of fission neutrons in the preceding generation.
- **the average number of fission neutrons emitted per neutron lost (absorption + leakage) in the system.**

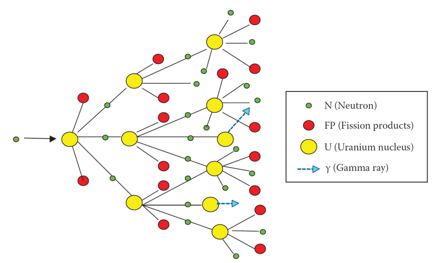


Figure 1: Fission chain reaction.

The fission chain reaction

What do we mean when we say a nuclear reactor is in a critical state?

- When the fission chain reaction is steady then $k = 1$ and the system is said to be **critical**. (The reactor power remains constant over time.)
- When the fission chain reaction (and so the power) grows over the successive generations (time) then $k > 1$ and the system is said to be **supercritical**.
- When the fission chain reaction (and so the power) decays over the successive generations (time) then $k < 1$ and the system is said to be **subcritical**.

What the reactor operator needs to do to increase the reactor power of a critical reactor?

- To increase the power of a reactor running at a steady power, the reactor must become supercritical temporarily.
- This is done by removing a part of a neutron-absorbing control rod from the reactor.
- When the required power is achieved then the reactor is set back to its critical state again (by adjusting the position of the control rod).

A similar process is followed when the operator wants to decrease the power - the difference is that the control rods are inserted into the core temporarily.

Control rods would usually be half-loaded into the core during normal operation in order to have the possibility to either remove them from the core or instert them further in the core, depending on the actual needs.

Nuclear reactor fuels

Nuclear reactor fuels

Can natural uranium serve as a nuclear fuel?

Yes. Natural uranium can be used in some reactors, but a majority of current reactors require fuel enriched in fissile material.

What materials are called fertile?

Fertile materials are non-fissile materials that can be converted into fissile by neutron absorption. For instance, it is possible to manufacture ^{233}U (from ^{232}Th) and ^{239}Pu (from ^{238}U) by the process known as **conversion**:

- $^{232}\mathrm{Th}(\mathrm{n},\gamma)^{233}\mathrm{Th} \rightarrow {}^{233}\mathrm{Pa}$ (Protactinium) $\rightarrow {}^{233}\mathrm{U}$
- $^{238}\mathrm{U}(\mathrm{n},\gamma)^{239}\mathrm{U} \rightarrow {}^{239}\mathrm{Np}$ (Neptunium) $\rightarrow {}^{239}\mathrm{Pu}$

(For the conversion to occur, it is sufficient to introduce the fertile materials into the reactor.)

Nuclear reactor fuels

Can you see some drawbacks in having ^{239}Pu present in nuclear fuel?

- Neutron capture on ^{239}Pu will lead to generation of higher nuclides of plutonium, americium, curium, etc. These contribute to the long-term radioactivity of the spent fuel.
- This problem can be, to some extent, reduced by using such fuel in fast reactors. The faster neutron energy spectrum increases the fission-to-absorption ratio.

Can you name some advantage of using ^{233}U + ^{233}Th fuel (thorium fuel cycle)?

The production of plutonium and higher radionuclides is practically eliminated in reactors that use the thorium fuel cycle.

What is the conversion (breeding) ratio C.

The conversion ratio is the average number of fissile atoms produced in a reactor per fissile atom consumed.

What reactors are called breeders?

- Breeder reactors are reactors with the conversion ratio $C > 1$.
- More than one fissile atom are produced per each fissile atom consumed.
- Breeders produce more fissile fuel than they consume.

What minimal value η (the average number of fission neutrons emitted per neutron absorbed in the fuel) must have in breeder reactors?

η need to be sufficiently larger than 2 in breeders.

What fissile nuclide has η sufficiently larger than 2 for thermal neutron energies?

For thermal neutron induced fission:

- ^{233}U has $\eta = 2.29$ (good enough), while
- ^{235}U has $\eta = 2.07$ and
- ^{239}Pu has $\eta = 2.07$ (not enough for thermal breeders due to parasitic neutron absorption).

Fast breeders have larger η.

Define the specific burnup of the fuel.

The specific burnup of the fuel is the total energy released in the fission of a unit mass of the fuel. It is usually measured in GWd/t of the heavy metal (including ^{238}U) originally contained in the fuel.

What is the average specific burnup of standard UO_2 fuel used in thermal reactors today?

The average burnup is over 45 GWd/t today. (It used to be around 35 GWd/MTU two decades ago.)

What is the typical material of the nuclear fuel?

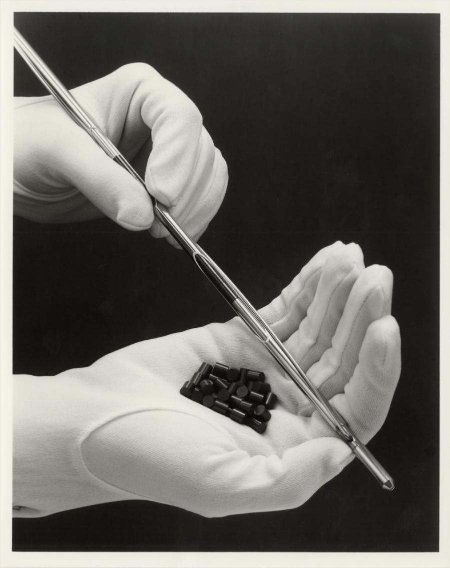
Nuclear fuel may be in various forms, most often it is the ceramic form of UO_2 (about $10 g/cm^3$), pressed into small pellets.

Figure 2: Ceramic fuel pellets.

Nuclear reactor fuels

Where are the fuel pellets placed?

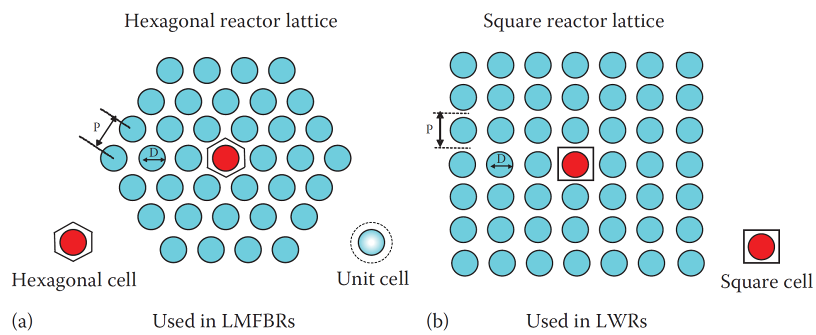
The UO_2 fuel pellets are placed in metallic tubes (fuel rods).



Nuclear reactor fuels

How are the fuel rods arranged geometrically?

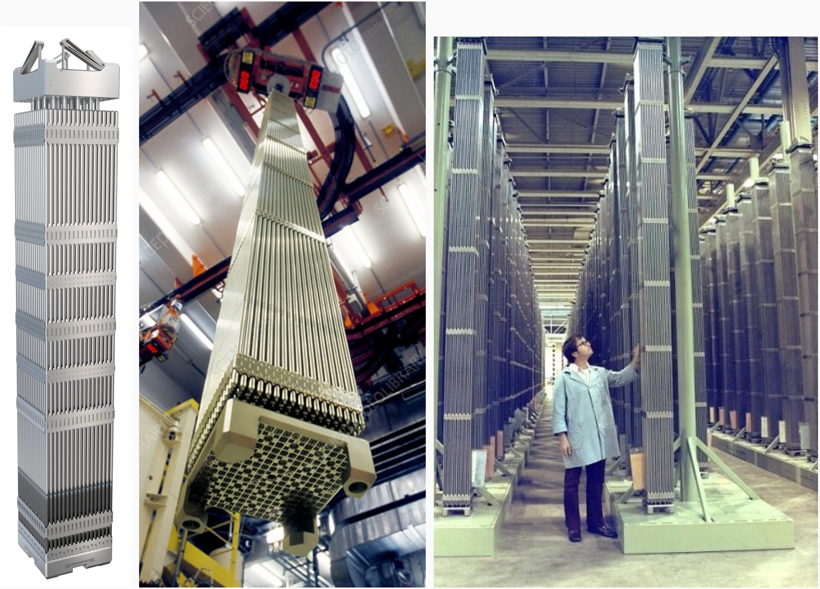
- A number of fuel rods are placed into a regular lattice formation to form a fuel assembly (FA).
- The lattice can be a square lattice or a triangular (also called hexagonal) lattice.
- The space between fuel rods serves for neutron moderation and fuel cooling.
- A forced coolant flow must be established through the fuel assemblies.



Nuclear reactor fuels

Figure 4: An example of a hexagonal fuel assembly.

Nuclear reactor fuels



Examples of square fuel assemblies.

How many FAs are placed in a typical reactor?

A large reactor is filled with hundreds of fuel assemblies.

Figure 5: A partly loaded active core.

Nuclear reactor fuels

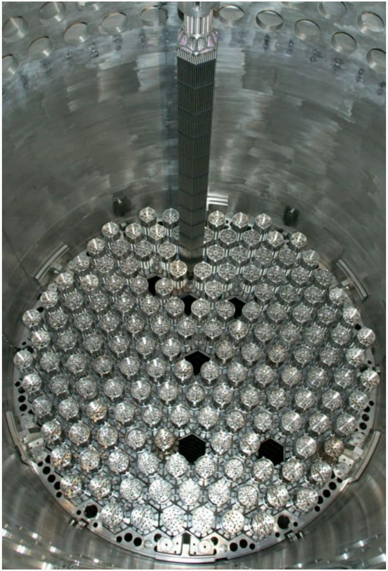


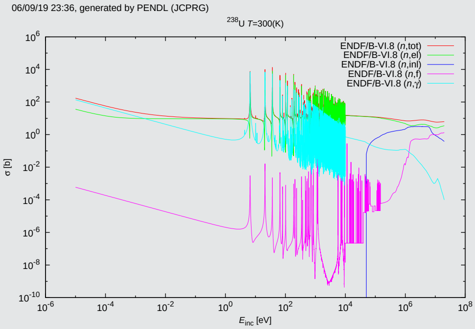
Figure 6: Almost all fuel assemblies loaded into the reactor.

Moderators

Moderators

Why is the moderator necessary in thermal nuclear reactors?

- The moderator is needed in thermal reactors to slow down neutrons effectively (over several collisions) to energies below the range of ^{238}U capture cross-section resonances (1eV-10keV).
- If the reactor didn't contain sufficient amount of the moderator then neutrons would be losing energy slowly over successive collisions and many of them would fall in the 1eV-10keV range and get captured on ^{238}U (not desirable).



Moderators

The ideal case of the neutron slowing-down process

- The fission neutrons travel trough the fuel while having large kinetic energies (2 MeV on average).
- Since the kinetic energy of fission neutrons is above the range of ^{238}U cross-section resonances the neutrons are not likely to be captured in ^{238}U.
- In order to reduce the capture of neutrons on ^{238}U, the neutrons returning from non-fuel materials to the fuel materials (like UO_2) should have kinetic energies below the ^{238}U capture cross-section resonance range.
- Ideally, fission neutrons leaving the fuel material would have several collisions in moderator, and return to the fuel as thermal neutrons.
- Without the moderator, neutrons would go through hundreds of collision, and at each collision the neutron speed would decrease only a little bit. There would be a large risk then that neutrons entering fuel would have energy in the resonance range and they would get captured.
- In reality, some neutrons still get captured on ^{238}U even when the system is well moderator.
- The fact that the neutron parasitic capture on ^{238}U is sensitive to the moderator amount can be used as a safety feature (this will be covered in a later lecture).

Moderators

Name some materials used as neutron moderators.

Light water, heavy water, graphite.

Fast reactors do not use any moderator. How can they work without any moderator?

In fast reactors, majority of neutrons that cause fission have energy above 10 keV (above the resonances in ^{238}U capture cross section).

How is that achieved?

This is achieved by the following three factors (that make fast reactors considerably more expensive than thermal reactors)

- Materials with light nuclides are not used. This is especially important for the coolant.
- Only metals with very small neutron capture cross-sections are used for construction of fuel assemblies. (As neutrons go through hundreds of collisions before they are absorbed, it is important that they are not absorbed in construction materials.)
- Also, the fuel must be enriched considerably more in its fissile content than fuel for thermal reactors to increase the chance that neutrons get absorbed in ^{235}U and cause fission.

Coolants

Coolants

Name some coolants used in thermal reactors.

- Light water (H_2O) - cheap, but H increases the undesirable parasitic capture of neutrons.
- Heavy water (D_2O) - expensive, but D does not capture neutrons as much as H.

Name some coolants used in fast reactors.

- Liquid metals (sodium, lead) - good cooling potential, but expensive and the cooling loop may freeze and break when not in operation (the cooling loop needs to be heated up electrically when not in use).
- Gasses (He, CO_2) - relatively low cooling potential due to small mass density (high pressure and flow rates are needed). Gas-cooled fast reactors have not been built yet due to challenges with structural materials that have to withstand fast-neutron damage and high temperatures up to 1600°C. (Only thermal gas-cooled reactors have all been built so far.)

Other components of nuclear reactors

Components of nuclear reactors

What purpose does the blanket serve in fast reactors?

The blanket is a region of fertile material surrounding the active core of breeder reactors. It is designed specifically for the fuel conversion/breeding.

What purpose does the reflector serve in the reactors?

- The reflector surrounds the blanket of the breeders or the active core of reactors that don't have blankets.
- The purpose of the reflector is to return the neutrons escaping from the active core back to the core.
- Neutrons leaving the active core undergo collisions in the reflector, and may change their direction back to the core.
- Reflectors should contain non-absorbing materials.

Components of nuclear reactors

What materials are control rods made from?

Control rods are made from boron steel, hafnium or cadmium - materials with large absorption cross sections. After several years, control rods lose their effectiveness and must be replaced.

What is the purpose of the reactor pressure vessel?

The pressure vessel contains all the reactor components and assures that the coolant is maintained under a sufficiently large pressure.

Why is large pressure needed in reactors that use pressure vessels?

The large pressure is needed for water and gas coolants to achieve a high temperature.

Why do we desire a high temperature of the coolants?

The higher the temperature of coolant is the more effective the conversion of heat to electricity becomes.

Power reactors

Power reactors

Power reactors are built with the purpose of producing heat or electricity. Are there other than power reactors?

- Research reactors (that can also source radionuclides for medical purposes)
- Training reactors (zero-power, power)
- Military reactors (sub or ship propulsion, plutonium production)
- Nuclear space propulsion

What are the current main types of power reactors?

Various reactors are possible with various combinations of fuel, moderator and coolant moderators.

- Thermal reactors:
  - Pressurised water reactors (PWR)
  - Boiling water reactors (BWR)
  - Heavy water reactors (HWR)
  - Gas-cooled reactors (GCR)
- Fast reactors:
  - Liquid metal fast breeder reactors (LMFBR)

Power reactors: PWR

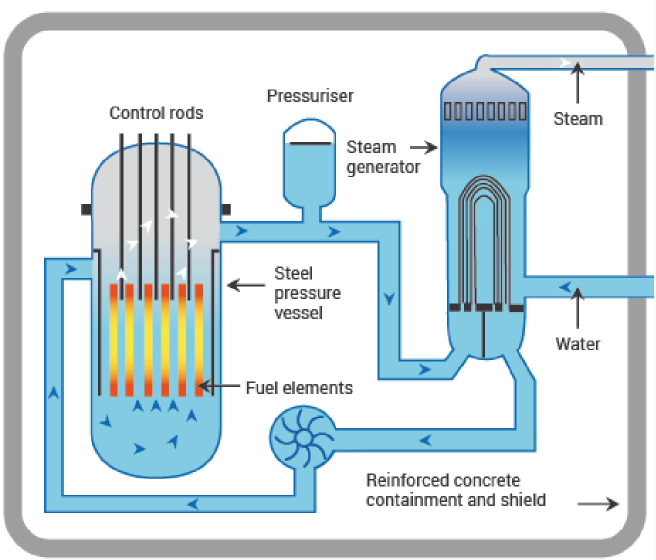


Figure 8: PWR and the primary cooling loop.

Power reactors: PWR

What are the pressure and temperature of the coolant in PWRs?

- Water inside the reactor is pressurised at about 15MPa, at temperatures 290-325 °C.
- Steam is generated at heat exchangers (steam generators) at the secondary cooling loop.
- A number of steam generators serves to a single PWR.

What is VVER?

VVER are Russian designed PWR. The hexagonal-shaped fuel assemblies have triangular lattice.

Western-design PWRs use square fuel rod lattice and square-shaped FAs.

Power reactors: BWR

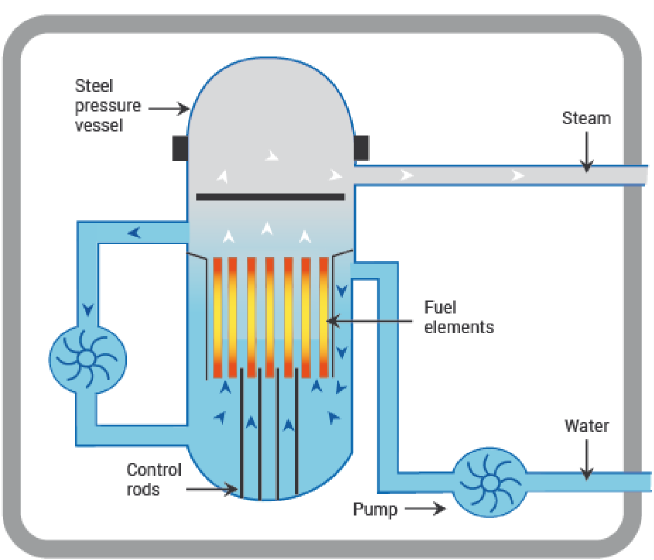


Figure 9: BWR and the primary cooling loop.

Power reactors: BWR

What are the pressure and temperature of the coolant in BWRs?

- Pressurised at about 7MPa, at temperature 290 °C.
- Water is recirculated inside the reactor (pumped from top to bottom).
- Steam is generated inside the reactor.
- Control rods enter the active core from the bottom of the core.
- Fuel sub-assemblies have fuel rods in square lattice hold by spacers and are enclosed in a shell. Usually, four sub-assemblies are bundled together. A control rods can slide in between the sub-assemblies.

What are advantages of BWR compared to PWR?

- Steam generated in the reactor, no need for steam generator.

What are disadvantages of BWR compared to PWR?

- Turbines, condensers, pumps and pipes over the whole loop become radioactive, which complicates the maintenance.
- Power density (W/cm^3) is smaller in BWR than in PWR, so the overall size of BWR is larger than PWR of a comparable power.

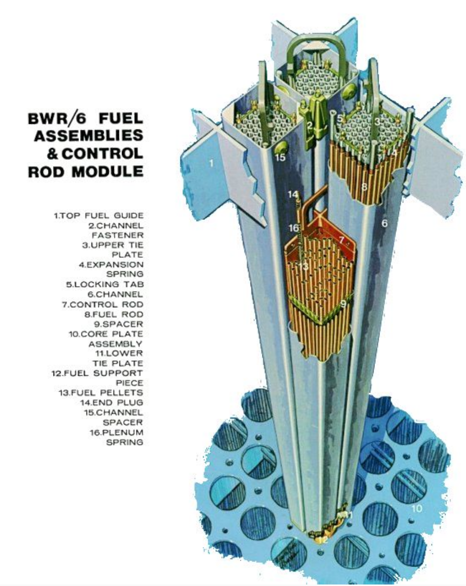


Figure 10: BWR FA

Power reactors: BWR

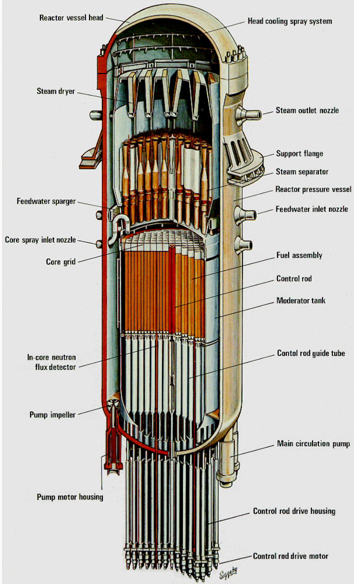


Figure 11: BWR

Power reactors: Heavy water reactors (HWR)

HWRs can be fuelled by natural uranium. Why?

HWRs can be fuelled by natural uranium thanks to low neutron absorption in heavy water (no enrichment needed).

The active core of HWR is larger than LWR. Why?

The active core of HWR is larger than LWR since a larger volume of heavy water is needed to moderate the reactor compared to LWR.

What is CANDU and what characteristics it has?

- CANDU is Canadian pressurised HWR.
- CANDU uses pressure tube concept.
- Hundreds of horizontal fuel tubes (pressurised at 10MPa with temperatures 266-310 °C) use D_2O coolant.
- For moderation purposes, the fuel tubes are placed inside a heavy water tank (under no pressure).
- CANDU can be refuelled during operation.

Power reactors: Heavy water reactors (HWR)

Figure 12: CANDU FA

Power reactors: Heavy water reactors (HWR)

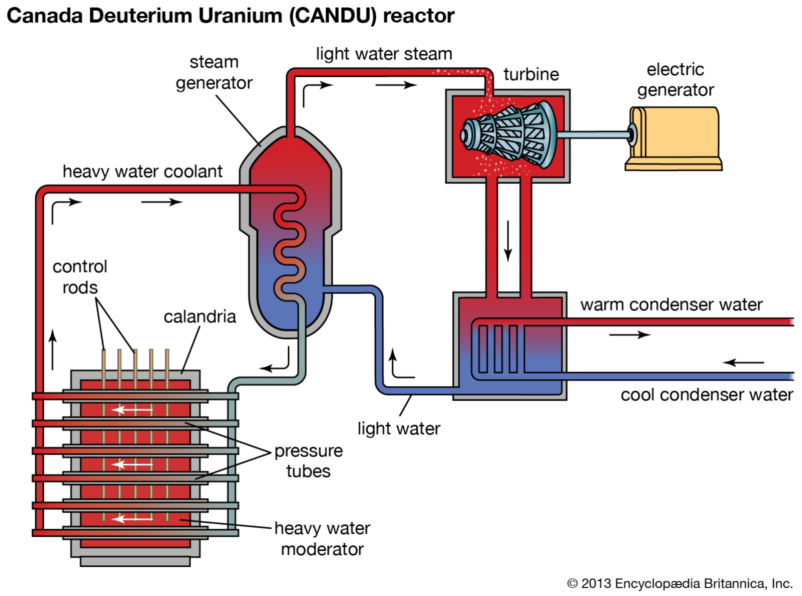


Figure 13: CANDU NPP

Power reactors: Gas-cooled reactors (GCR)

Are GCR thermal or fast reactors?

They can be either. If they contain a moderator (e.g. graphite) then the neutron energy spectrum is thermalised. A GCR without a moderator would be a fast reactor.

What is the major advantage of GCR?

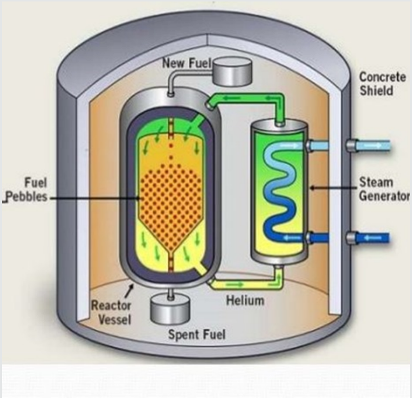
- The major advantage of GCR is that the gas, e.g. CO_2, can achieve a relatively high temperature of 540 °C at 16 MPa.
- Therefore, GCR can achieve an overall efficiency of about 40%.

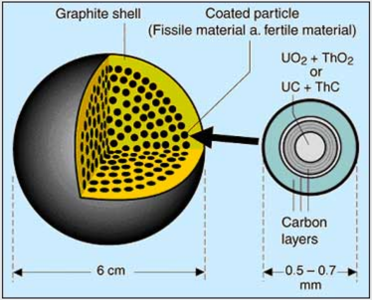
Some GCRs:

- British advanced gas reactor (AGR): CO_2 cooled, graphite moderated.
- US designed and built high-temperature gas-cooled reactors (HTGR): helium-cooled (up to 870 °C, 50% efficiency), graphite moderated, fuel with thorium.
- Other countries built a number of HTGR reactors, including Germany, Japan and China (pebble-bed design).

Power reactors: Gas-cooled reactors (GCR)

Pebble bed reactor and fuel design





Power reactors: Liquid metal fast breeder reactors (LMFBR)

What is the major advantage of fast reactors?

The capability to breed the fuel.

What is the common option for the coolant in LMFBR?

Sodium. Other metals have been also tried, including mercury, lead, bismuth.

Is heavy pressure vessel needed for LMFBR?

No. Sodium can achieve up to 882 °C without boiling at atmospheric pressure.

What is the disadvantage of the sodium coolant?

- The melting point is 98 °C, so the entire coolant system must be kept heated at all times to prevent the sodium from getting solid.
- Sodium reacts with water chemically, which raises risks of failure in steam generators.
- Sodium that passes through the core becomes radioactive (^{24}Na is produced by neutron capture with half-life of 15 hours).
- The risk of having a radioactive leak in the steam generator is removed by introducing an intermediate sodium loop (so, LMFBR have two sodium loops).

Power reactors: Liquid metal fast breeder reactors (LMFBR)

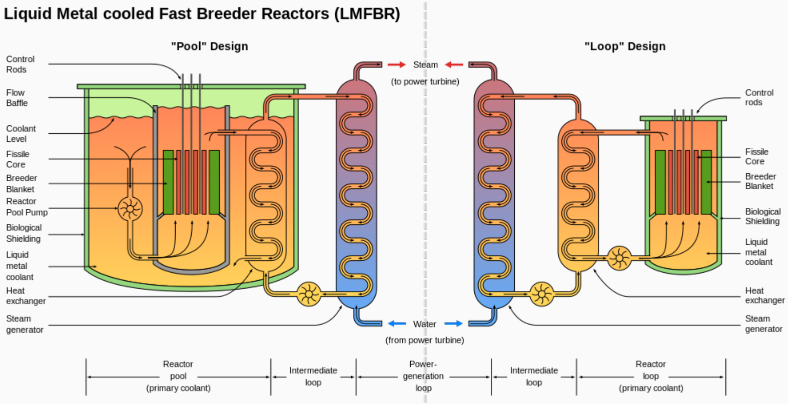


Figure 14: LMFBR