LECTURE 4
NUCLEAR POWER PLANT

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Topics

A.2.1	**Nuclear Energy Fundamentals**
A.2.2	**Nuclear Reactors: Types, Components and Layout**
A.2.3	**Nuclear Fuel Cycle and Environmental Effects**
A.2.4	**Case Study: Rooppur Nuclear Power Plant**

Nuclear Fuel Cycle

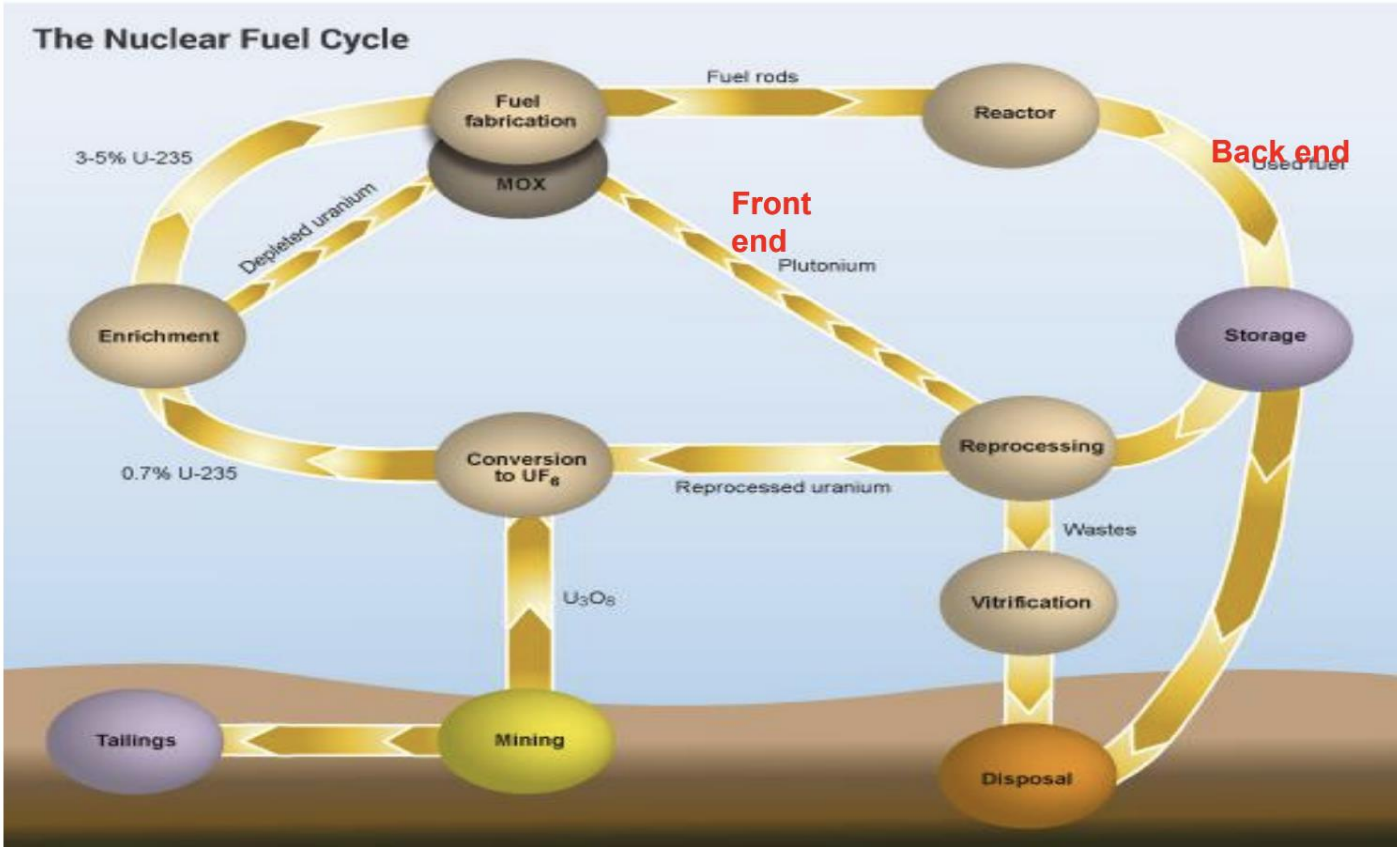
- The nuclear fuel cycle is the series of industrial processes which involve the production of electricity from uranium in nuclear power reactors.
- Uranium is a relatively common element that is found throughout the world. It is mined in a number of countries and must be processed before it can be used as fuel for a nuclear reactor.
- Fuel removed from a reactor, after it has reached the end of its useful life, can be reprocessed so that most is recycled for new fuel.
- To prepare uranium for use in a nuclear reactor, it undergoes the steps of mining and milling, conversion, enrichment and fuel fabrication. These steps make up the 'front end' of the nuclear fuel cycle.
- After uranium has spent about three years in a reactor to produce electricity, the used fuel may undergo a further series of steps including temporary storage, reprocessing, and recycling before wastes are disposed. Collectively these steps are known as the 'back end' of the fuel cycle.

Front end:

- mining extraction
- enrichment and fuel fabrication

Back end:

- Spent fuel Reprocessing, Re-cycling and
- Disposal

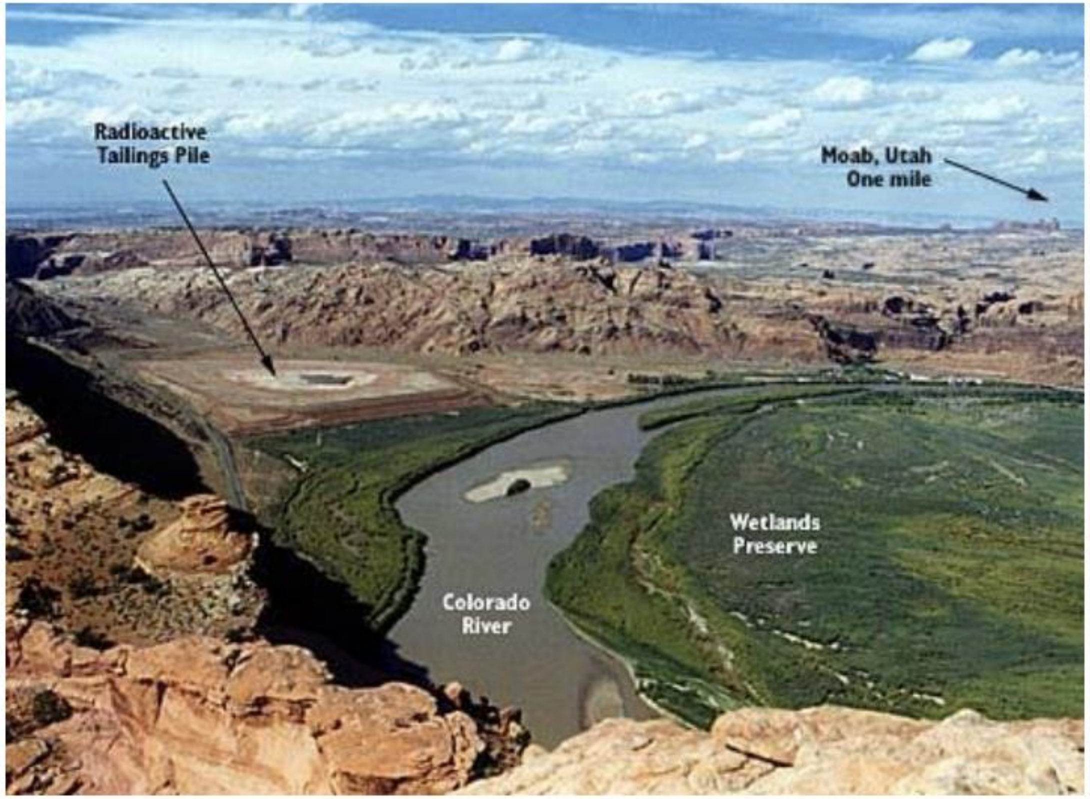

The Nuclear Fuel Cycle
Fuel rods
Fuel fabrication
Reactor
Back end
Used fuel
3-5% U-235
MOX
Depleted uranium
Front end
Plutonium
Enrichment
Storage
Conversion to UF_6
Reprocessing
0.7% U-235
Reprocessed uranium
Wastes
U_3O_8
Vitrification
Tailings
Mining
Disposal

Uranium mining

- Uranium is a slightly radioactive metal that occurs throughout the earth's crust. It is about 500 times more abundant than gold and about as common as tin. It is present in most rocks and soils as well as in many rivers and in sea water.
- Economically feasible deposits of the ore, pitchblende, U3O8, range from 0.1% to 20%.
- Open pit mining is used where deposits are close to the surface. Underground mining is used for deep deposits, typically greater than 120 m deep.
- In situ leaching (ISL), where oxygenated groundwater is circulated through a very porous ore body to dissolve the uranium and bring it to the surface. ISL may use slightly acidic or alkaline solutions to keep the uranium in solution. The uranium is then recovered from the solution.
- After extraction, U3O8 (Uranium Oxide) is processed in the from of compressed powder called yellow cake. About 200 tones of called yellow cake is annually necessary for running a1000 MWe nuclear power plant.
- For 1 pound of uranium, more than 200 pounds of byproduct material, tailings, are typically produced.
- After extraction of uranium from the ore, the tailings contain much of their original radioactivity.

Uranium mining

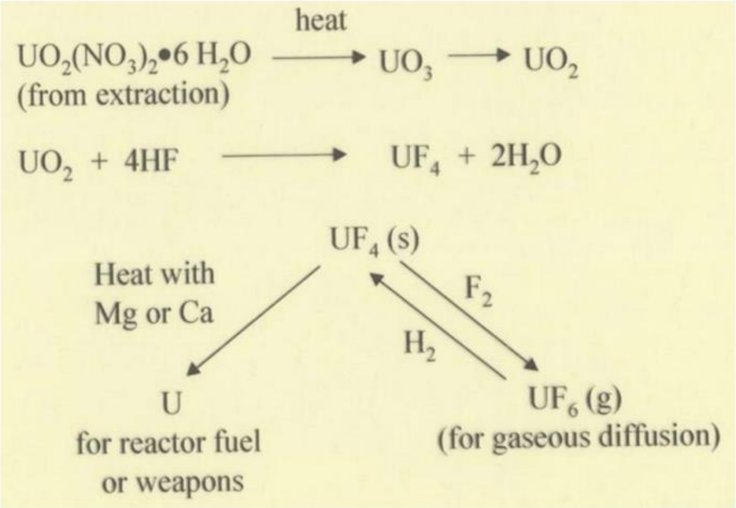
- Toxic heavy metals, including chromium, lead, molybdenum, and vanadium, are also present in this byproduct material in significant, concentrations.

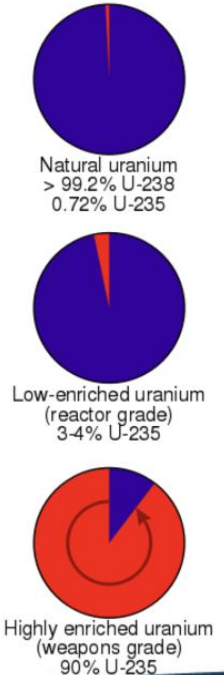


Mechanical Engineering

Uranium Enrichment and Fuel Fabrication

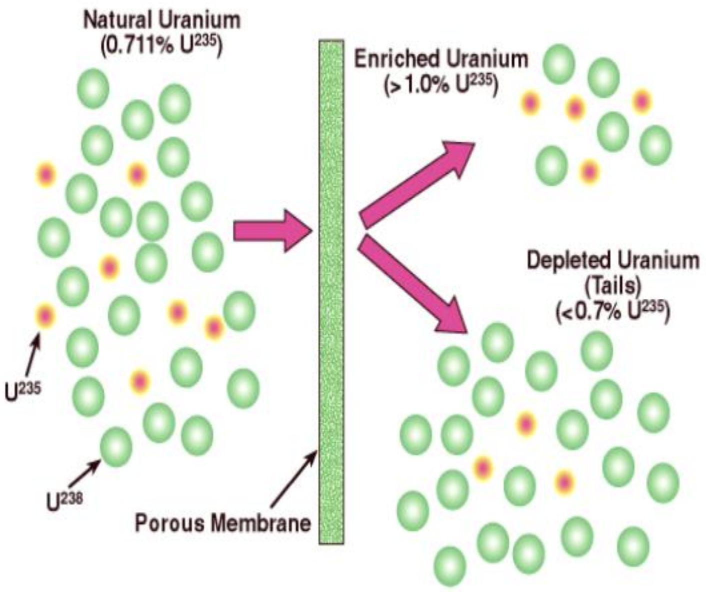
- Milled uranium ore—U_3O_8 or "yellowcake"—is dissolved in nitric acid, yielding a solution of uranyl nitrate $UO_2(NO_3)_2$.
- Reduction with hydrogen gives UO_2, which is converted with hydrofluoric acid (HF) to uranium tetrafluoride, UF_4.
- Oxidation of UF_4 with fluorine yields UF_6 that is commercially known as **Hex.**
- Enriched **UF_6 must be converted back** to solid uranium or uranium oxide



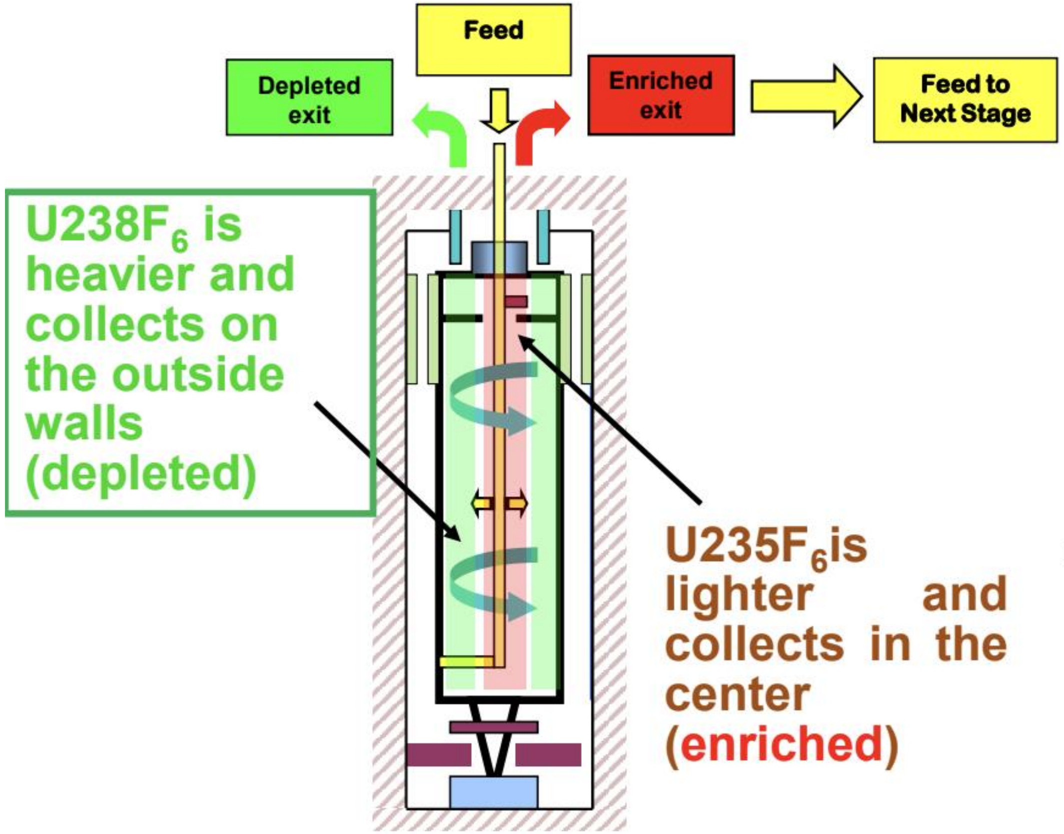


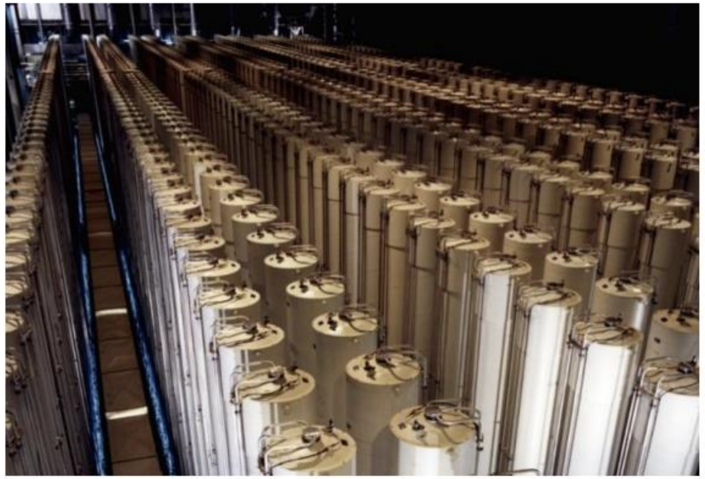
Uranium Enrichment: Gas Diffusion

- Higher concentration of fissionable U-235 isotope is necessary for nuclear reaction.
- Both U-235 and U-238 have the same chemical properties, enrichment requires a physical process. Key factor is U-238 is slightly heavier than U-235.
- The two method of uranium enrichment are:
  - Gaseous diffusion (older)
  - Centrifugation (newer)
- Both enrichment techniques use small differences in the masses (< 1%) of the U-235F6 and U-238F6 molecules to increase the concentration of U-235.
- A production of 1 ton of 3.5% enriched Uranium-235 could leave 6 tones of depleted Uranium.
- Gaseous diffusion is a uranium enrichment process based on the difference in rates at which uranium isotopes in the form of gaseous uranium hexafluoride (UF6) diffuse through a porous barrier.
- The rate of diffusion of a gas is inversely proportional to the square root of the mass. As U-235 is lighter than U-238, so it diffuses easily through the porous barrier.



Uranium Enrichment: Gas Centrifuge





- The separation of **uranium** requires the **uranium** hexafluoride (UF_6) in **gaseous** form to be entered in the **centrifuge** cylinder where the UF_6 **gas** is rotated at a high speed generally **in excess of 50000 rpm**.

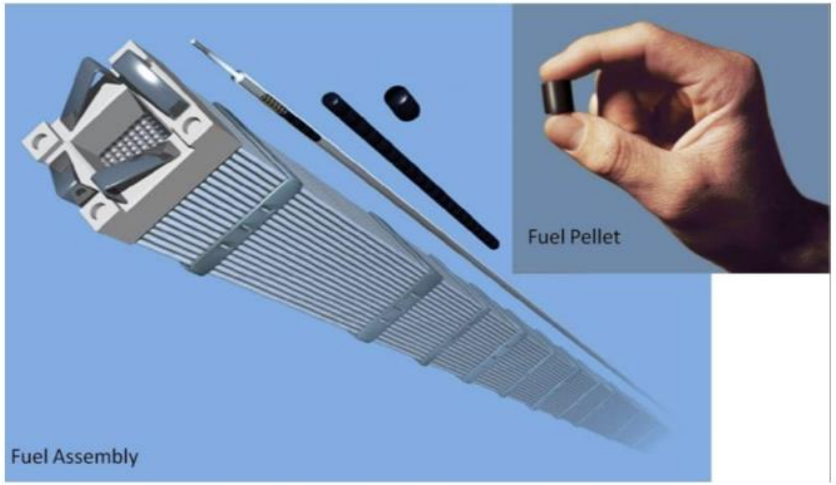
Uranium Enrichment: Gas Diffusion Vs. Gas Centrifuge

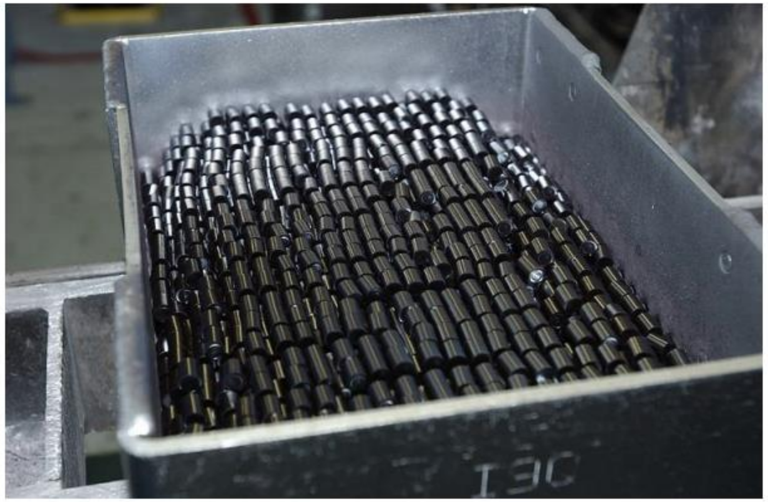
- Three distinct characteristics of the gas centrifuge process has made it economically attractive for uranium enrichment over gas diffusion:

  - Proven technology: Centrifuge is a proven enrichment process, currently used in several countries.
  - Low operating costs: Its energy requirements are less than 5% of the requirements of a comparably sized gaseous diffusion plant.
  - Modular architecture: The modularity of the centrifuge technology allows for flexible deployment, enabling capacity to be added in increments as demand increases.

Fuel Fabrication

- Reactor fuel is generally in the form of ceramic pellets.
- These are formed from pressed uranium oxide which is sintered (baked) at a high temperature such as over 1400°C.
- The pellets are then encased in metal tubes to form fuel rods, which are arranged into a fuel assembly ready for introduction into a reactor.





Spent Fuel

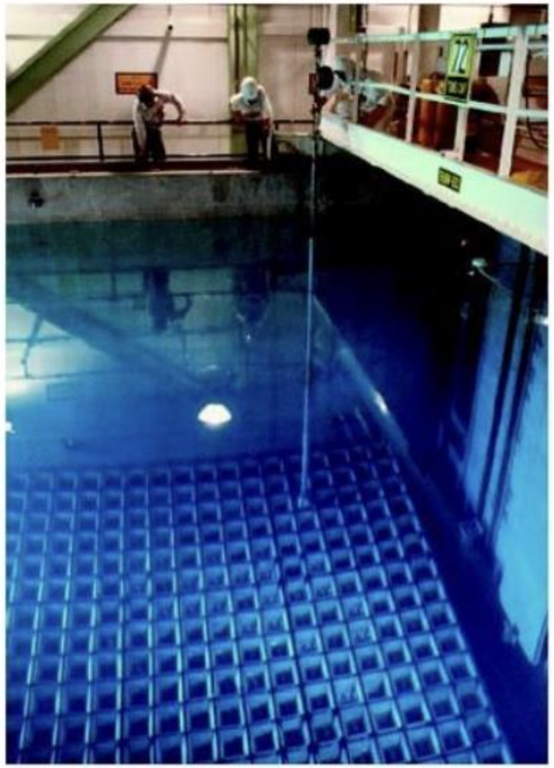
- No reactor fully burns all the U-235 in its fuel.
- Fuel rods are replaced as fission products and actinides build up with time causing the “poisoning” of the fuel.
- Replacement details differ for different types of reactor.
- Fuel rods are replaced in regular intervals typically a third in a year in PWRs.

Material	Initial Fuel	Spent Fuel
Transuranic elements	0.000	0.065%
U-236	0.000	0.46%
Pu isotopes	0.000	0.89%
Fission products	0.000	0.35% (High Level Waste)
U-235	3.3%	0.08%
U-238	96.7%	94.3%

Transuranic elements: The chemical *elements* with **atomic numbers greater than 92** (the atomic number of uranium). All of these *elements* are unstable and decay radioactively into other *elements.*

Spent Fuel and Spent Fuel Direct Disposal

- As the spent fuel initially remains very radioactive as well hot soon after its removal from reactor it is placed under few meters of water pool equipped with cooling system for at least one year.



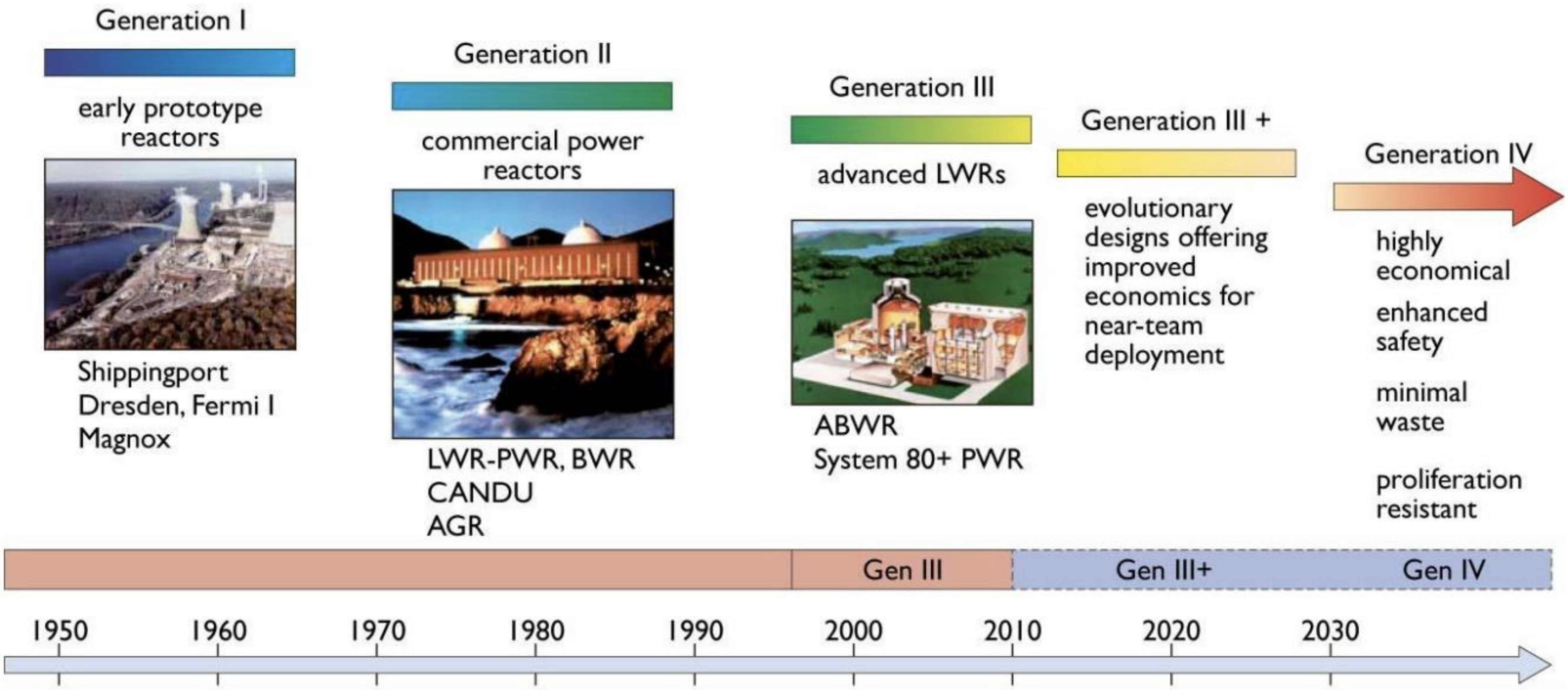
Spent Fuel Direct Disposal

- The spent fuel is then moved to subsequent treatment: direct disposal and reprocessing.
- The radioactive waste arising from the nuclear power industry is classified as:
  - High Level Waste:
  - Intermediate Level Waste
  - Low Level Waste.
- High Level Waste (HLW)
  - High Level Waste is mainly either spent reactor fuel or the separated fission products and actinides that results from reprocessing. These wastes require shielding, cooling and needs to be monitored for long time say 50 years followed by burial in deep underground stores. The most troublesome high level waste are Neptunium-237 (half-life two million years) and Plutonium-239 (half-life 24,000 years).
  - In order to store the high level radioactive waste in long-term geological depositories, specific waste forms process (glass waste form/ceramic waste form) need to be used which will allow the radioactivity to decay away retaining their integrity for thousands of years.
- Intermediate Level Waste
  - Intermediate Level Waste also mainly comes from reactor and assumes approximately one tenth of the total volume and one twentieth of total radioactivity. Intermediate level waste is generated during operation of a nuclear power plant – consists mostly of ion exchange resins used to clean the water circulating through the reactor.

Spent Fuel Direct Disposal

- Low Level Waste
  - Low Level Waste mainly materials and equipment that have become contaminated by radioisotopes.
  - It assumes approximately nine tenth of the total volume of the radioactive materials but contribute to less than 1% of total radioactivity.
  - This kind of waste is also a subject of burial.
  - The Spent fuel removed from a reactor still contain significant amount of fissile U-235 and Plutonium-239 and Plutonium-240.
  - Reprocessing is designed to extract these fissile materials for reuse.
  - The spent fuel is moved from the reactor site to the reprocessing plant. Prior to reprocessing, the spent fuel is kept in cooling pool for five years so that uranium, plutonium and waste become chemically separable.
  - France, UK, Japan, and Russia currently reprocess spent fuel.

Trend of Nuclear Power Technology



Trend of Nuclear Power Technology

- At present: 60% PWR, 20% BWR.
- Most of the reactor in use today is of Generation II having economic life of 40 years.
- Generation III offered evolutionary improvements of Generation II in the areas of fuel technology, thermal efficiency, modularized construction, safety systems (especially the use of passive rather than active systems), and standardized design. Improvements in Gen III reactor technology have aimed at a longer operational life, typically 60 years of operation, potentially to greatly exceed 60 years, prior to complete overhaul and reactor pressure vessel. Replacement.
- Gen III+ reactor designs are an evolutionary development of Gen III reactors, offering significant improvements in safety over Gen III reactor designs. Examples of Gen III+ designs include:
  - VVER-1200/392M Reactor of the AES-2006 type
  - Advanced CANDU Reactor (ACR-1000)
- Generation IV designs represent more advanced reactor design for deployment after 2030 with radical change in reactor design and or fuel handling.

Advantages of Nuclear Power

- The generation of electricity through nuclear energy reduces the amount of energy generated from fossil fuels (coal and oil) therefore lowering greenhouse gas emissions (CO2 and others).
- Another advantage is the required amount of fuel: less fuel offers more energy. It represents a significant save on raw materials but also in transport, handling and extraction of nuclear fuel. The cost of nuclear fuel (overall uranium) is 20% of the cost of energy generated.
- The production of electric energy is continuous. A nuclear power plant is generating electricity for almost 90% of annual time. Moreover, nuclear power does not depend on natural aspects. It's a solutions for the main disadvantage of renewable energy, like solar energy or wind energy.
- By reducing the consumption of fossil fuels nuclear power also improve the quality of air affecting the disease and quality of life.

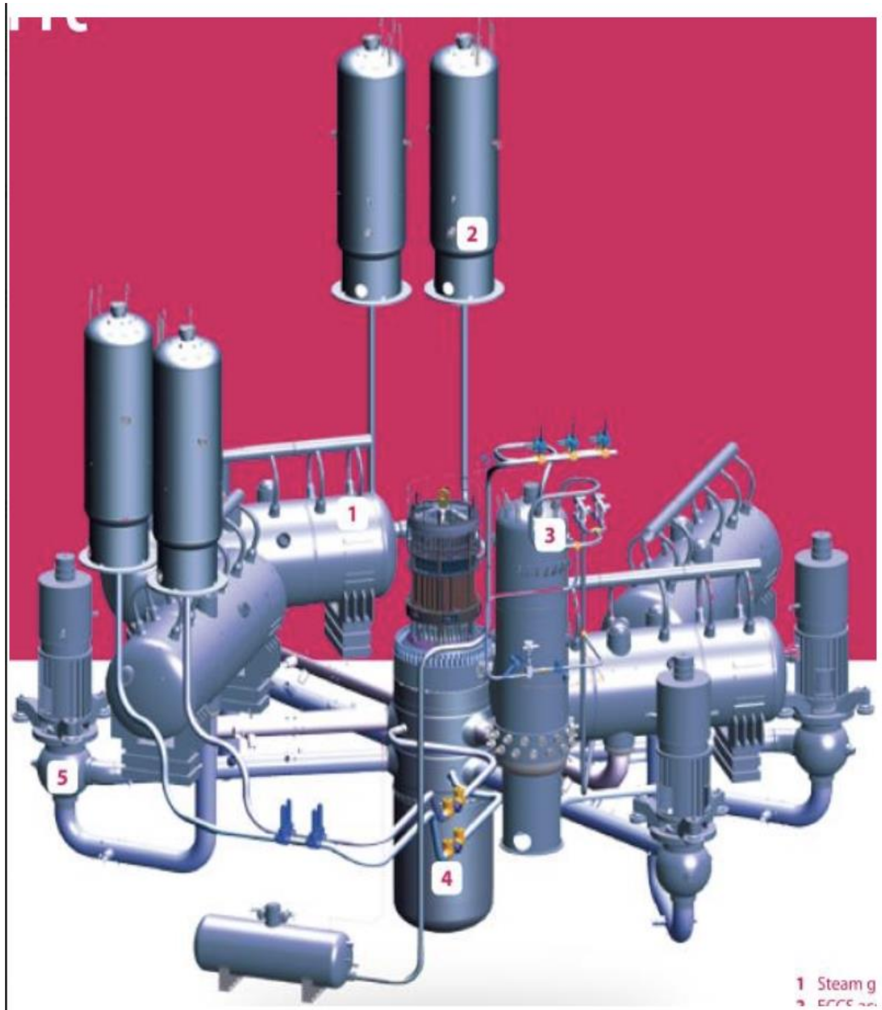
Disadvantages of Nuclear Power

- Despite the high level of sophistication of the safety systems of nuclear power plants, the human aspect has always an impact. Facing an unexpected event or managing a nuclear accident we don't have any guarantee that decisions we took are always the best.
- One of the main disadvantages is the difficulty in the management of nuclear waste. It takes many years to eliminate its radioactivity and risks.
- Nuclear plants have a limited life. The investment for the construction of a nuclear plant is very high and must be recovered as soon as possible, so it raises the cost of electricity generated.
- Nuclear power plants generate external dependence. Not many countries have uranium mines and not all the countries have nuclear technology, so they have to hire both things overseas.
- Current nuclear reactors work by fission nuclear reactions. These chain reactions is generated in controlled way, however in case the control systems fail, generating continuous reactions causing a radioactive explosion that would be virtually impossible to contain.
- Probably the most alarming disadvantage is the use of the nuclear power in the military industry.

Nuclear Power in Bangladesh

- Rooppur Nuclear Power Plant is an under-construction 2.4 GWe nuclear power plant in Bangladesh.
- The nuclear power plant is under construction at Rooppur, Paskey in the Ishwardi Upazila of Pabna District, on the bank of the river Padma.
- It will be the country's first nuclear power plant, and the first of two units is expected to go into operation this year!
- It is to be built by the Russian Rosatom State Atomic Energy Corporation.
- The Water-Water Energetic Reactor (VVER) i.e. water-cooled water-moderated energy reactor is a series of pressurized water reactor (PWR) designs originally developed in the Soviet Union, and now Russia.
- VVER were originally developed before the 1970s, and have been continually updated. VVER is associated with a wide variety of reactor designs spanning from generation I reactors to modern generation III+ designs with power output ranges from 70 to 1200 MWe, with designs of up to 1700 MWe in development.

Nuclear Power in Bangladesh



VVER reactors are PWR's however, they have some distinguishing features compared to other PWRs such as:

- **Horizontal steam generators**
- **Hexagonal fuel assemblies**
- **No bottom penetrations in the pressure vessel**
- **High volume pressurizers assuring a high level of reactor safety owing to the large coolant inventory in the primary circuit**

1 Steam generator
2 ECCS accumulator
3 Pressurizer
4 Reactor pressure vessel
5 Reactor coolant pump

Nuclear Power in Bangladesh

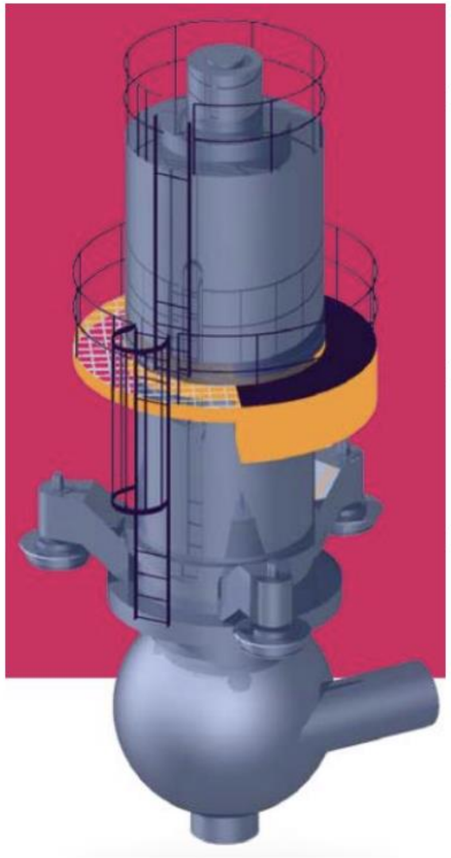
1 Control and protection system drives
2 Vessel head
3 Outlet nozzle
4 Inlet nozzle
5 Core baffle
6 Fuel assemblies

VVER Reactor Core

The design service life of the reactor pressure vessel is 60 years, with maximum neutron flux of 4.22×10^{19} neutron/cm^2 (> 0.5 MeV).
Measures to extend vessel service life have included:

- limitation of nickel content in welds;
- limitation of impurities in base metal and welds;
- decrease in ductile to brittle transition temperature of the nozzle area shell material and
- reduction of neutron flux at vessel walls by increasing vessel diameter.

Nuclear Power in Bangladesh



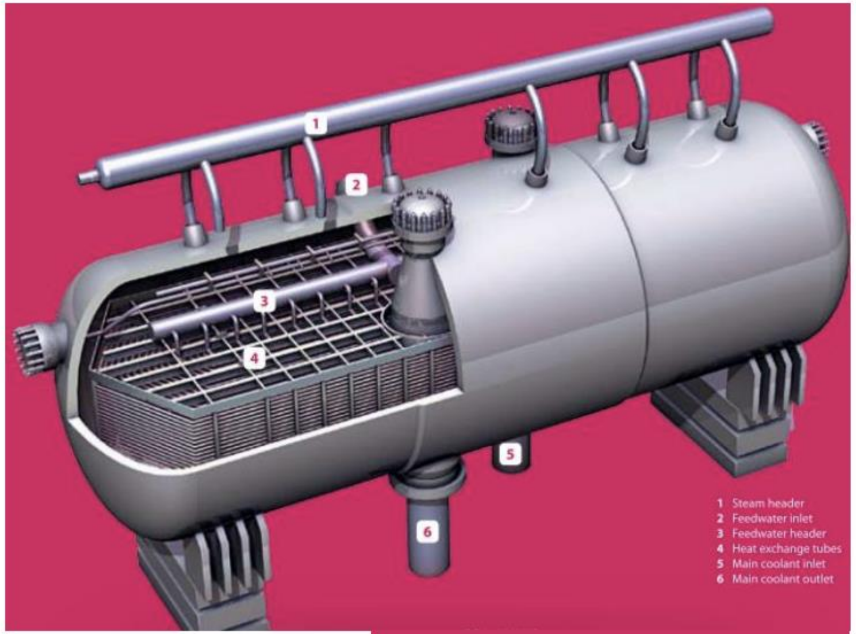
VVER Primary Coolant Pump

- It’s a vertical pump set, consisting of a **centrifugal single-stage pump** with a mechanically sealed shaft and spherical welded-forged casing and asynchronous two-speed electric motor with a flywheel.

- The cooling of pump motor and lubrication of all bearings is provided by **water**

- Basic data for the primary coolant pump is: capacity, **22000 m^3/h**; Head, **0.588 MPa**; Nominal suction pressure, **16.02 MPa**; rpm: 1000; Power consumption, **5-6.8 MW** ; service life, 60 years.

Nuclear Power in Bangladesh



1 Steam header
2 Feedwater inlet
3 Feedwater header
4 Heat exchange tubes
5 Main coolant inlet
6 Main coolant outlet

VVER Steam Generator

Horizontal steam generators are traditionally used in VVER reactors.

Due to horizontal design, the steam generators do not face such problems as **primary water stress-corrosion cracking, fouling and Denting**.

The heat transfer surface of the steam generator consists of **10 978 stainless** steel tubes of 16 mm diameter and 1.5 mm wall thickness.

The heat exchange tubes are arranged in a **U-shaped bundle**. The “corridor” layout of the tubes has vertical spacings of 22 mm and 24 mm horizontally.

ECCS (Emergency Core Cooling System)

All nuclear power plants have some form of **emergency makeup water system** in the event that normal makeup is lost and a major break occurs in the reactor cooling system (**LOCA: Loss Of Coolant Accident**). These emergency systems are called such names as:

High Pressure Coolant or Safety Injection, Low Pressure Coolant or Safety Injection, Reactor Core Injection Cooling.

The Emergency Core Cooling Systems have 1 major function:

- **Provide makeup water to cool the reactor** in the event of a loss of coolant from the reactor cooling system. This cooling is needed to remove the **decay heat** still in the reactor's fuel after the reactor is shutdown

The Emergency Core Cooling Systems, in some plants may have a second major function:

- **Provide chemicals** to the reactor and reactor cooling system to ensure the reactor does not produce power.

The Emergency Core Cooling Systems comprised of **pumps, accumulator tanks and piping**

VVER-1200: Working principle

- Reactor fuel rods are fully immersed in water kept at **15 MPa pressure (Primary Cooling Circuit)** so that it does not boil at the normal **(220 to over 300 °C)** operating temperatures.
- Water in the reactor serves both **as a coolant and a moderator** which is an important safety feature. Should coolant circulation fail, the **neutron moderation effect of the water diminishes**, reducing reaction intensity and compensating for loss of cooling, a condition known as **negative void coefficient**. Later versions of the reactors are encased in massive steel pressure shells.
- **Fuel is low enriched (2.4–4.95% U_{235}) uranium dioxide (UO_2)** or equivalent pressed into pellets and assembled into fuel rods.
- **Reactivity is controlled by control rods** that can be inserted into the reactor from above. These rods are made from a neutron absorbing material and, depending on depth of insertion, hinder the chain reaction. If there is an emergency, a reactor shutdown can be performed by full insertion of the control rods into the core.
- VVER reactor is have **several cooling circuit** such as Primary (Reactor Cooling), Secondary (Steam Generator), Tertiary (Condenser Cooling) etc.
- design service life of the reactor **up to 60 years**