

Reactor Operations, Fuel Cycles, and Secondary Systems

By William Richards and Riley Madden



School of Nuclear Engineering

Neutronics Review

- In general, reactors are characterized by their choice of 3 different materials: fuel, coolant, and moderator
- Fuel – Made of a fissile material, where the fission chain reaction actually occurs
- Coolant – Any material which removes heat from the primary system (the core) and transfers it to the secondary system (steam generator, turbine, etc.)
- Moderator – Material within the core used to slow neutrons from fast to thermal energies
- In many reactor designs, the moderator and coolant may be the same material
- Additionally, reactors will have control elements used to accelerate and slow the chain reaction

$$k_{\infty} = \frac{\nu \Sigma_f \phi}{\Sigma_a \phi} \quad \text{■} - \Sigma_s \phi$$

$\nu \Sigma_f \phi, \Sigma_a \phi$ $\Sigma_f \phi, \Sigma_a \phi$



Fuel Material



Control Material



Moderator



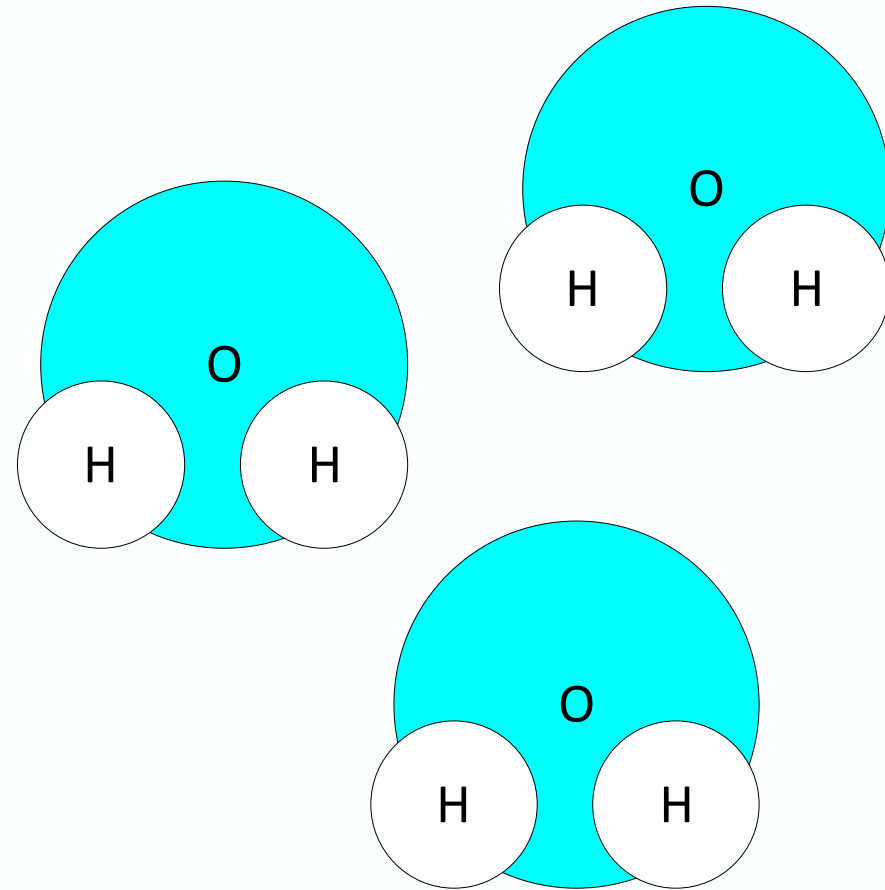
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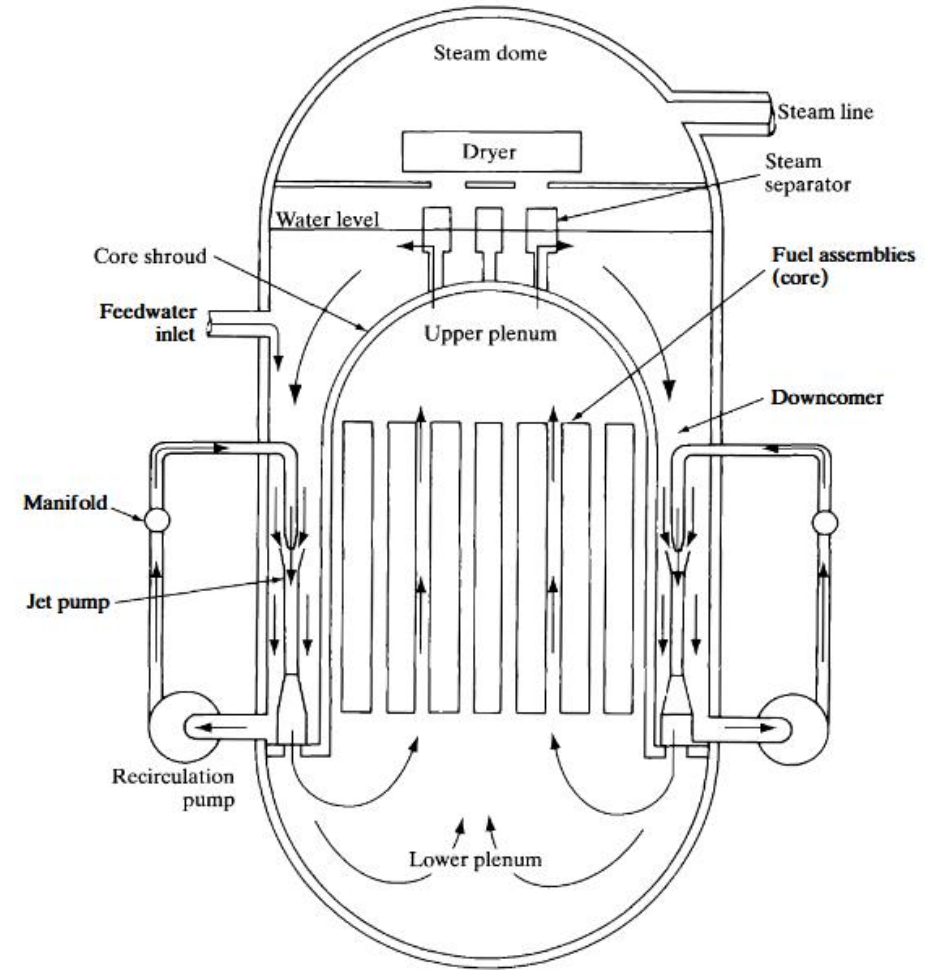
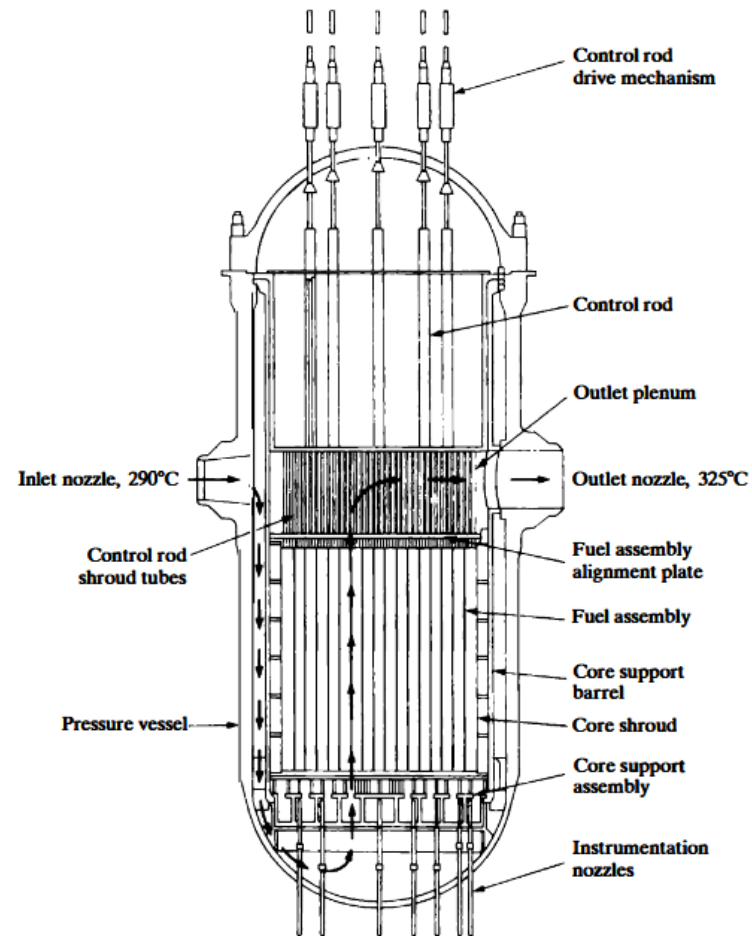
Standard Light Water Designs

What is “Light Water Design?”

- “Designs that use light water (H_2O) as their coolant”
- Every power reactor built in the United States uses one of two designs
 - Pressurized Water Reactor
 - Boiling Water Reactor
- Use heat from fission to boil water, turn turbine, make power

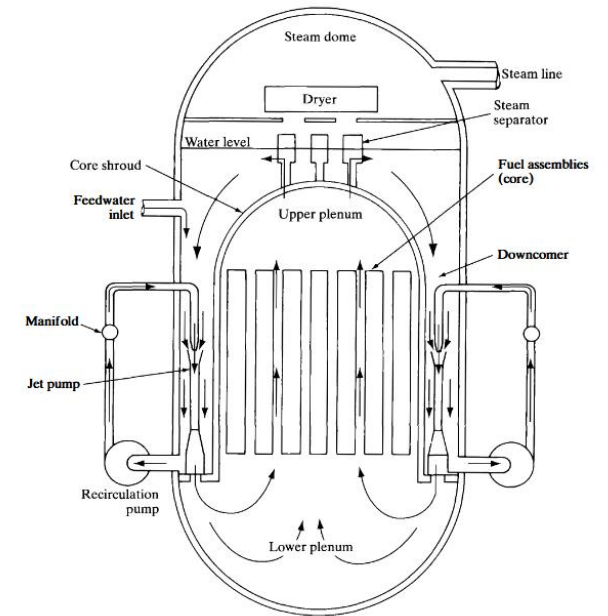
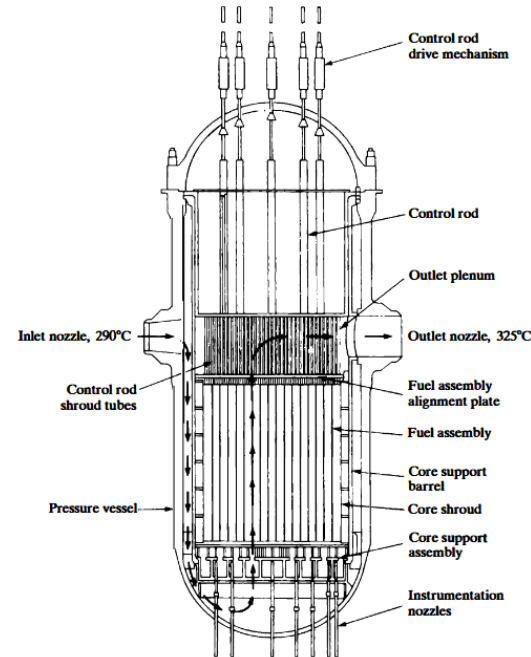


Reactor Vessel



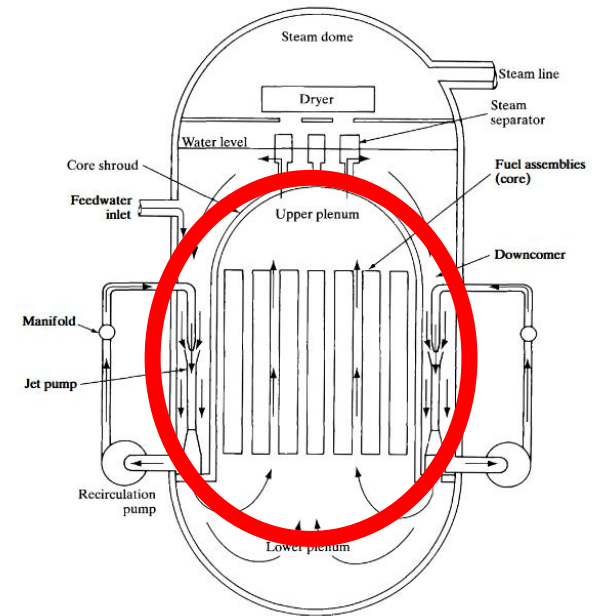
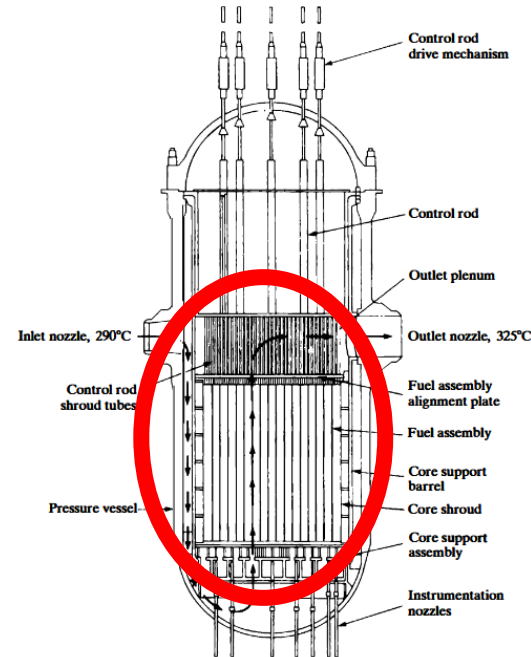
Reactor Vessel

- Thick steel container, capable of withstanding high temperature, pressures, and corrosion
- Coolant flows into the reactor vessel, through the core, then out as either hot water or steam



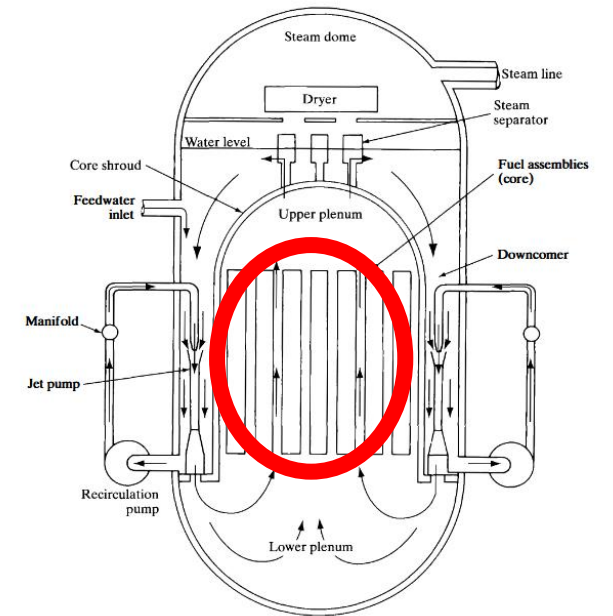
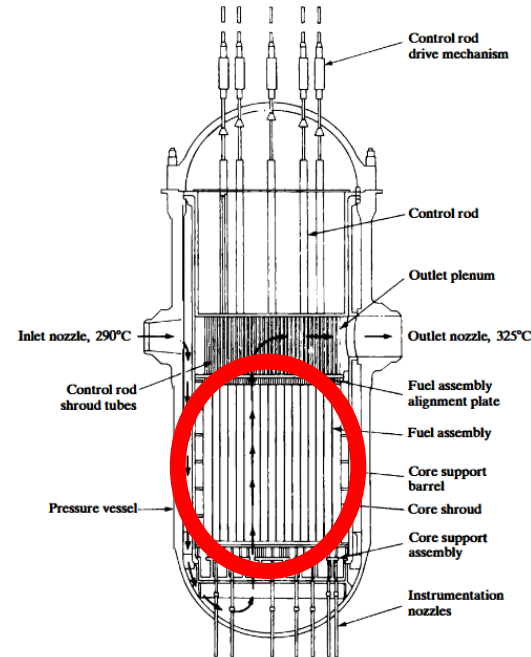
The Core

- Thin, stainless steel cylinder designed to force water down the outside, and up through the inside
- Contained within the core shroud
- Contains the fuel assembly



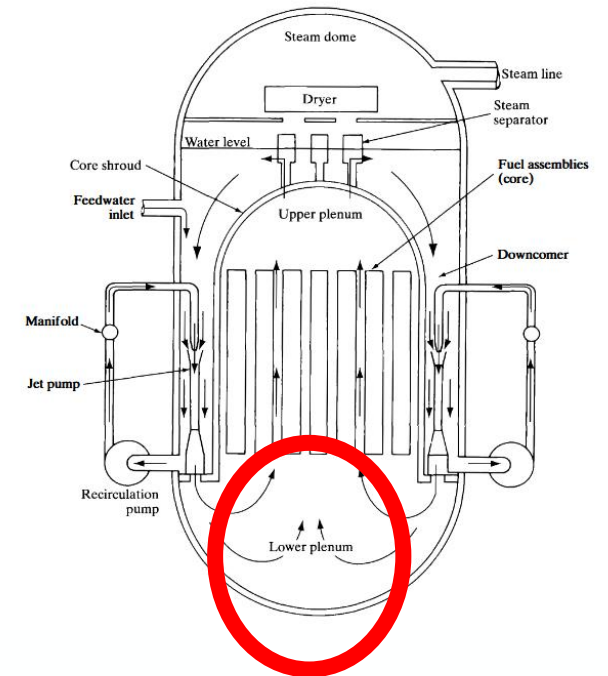
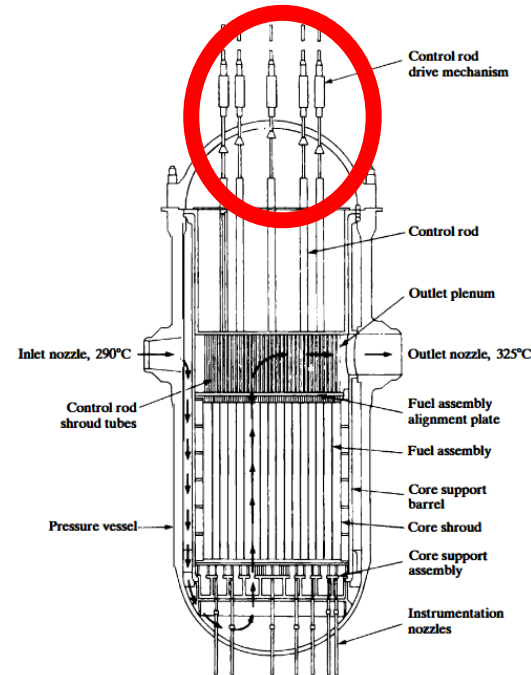
Fuel Assembly

- Array of hundreds of rods filled with pellets of Uranium fuel
- Uranium pellets covered with cladding – a ceramic/metallic shell to contain fission products and increase heat transfer
- Coolant flows through gaps to take heat from the core



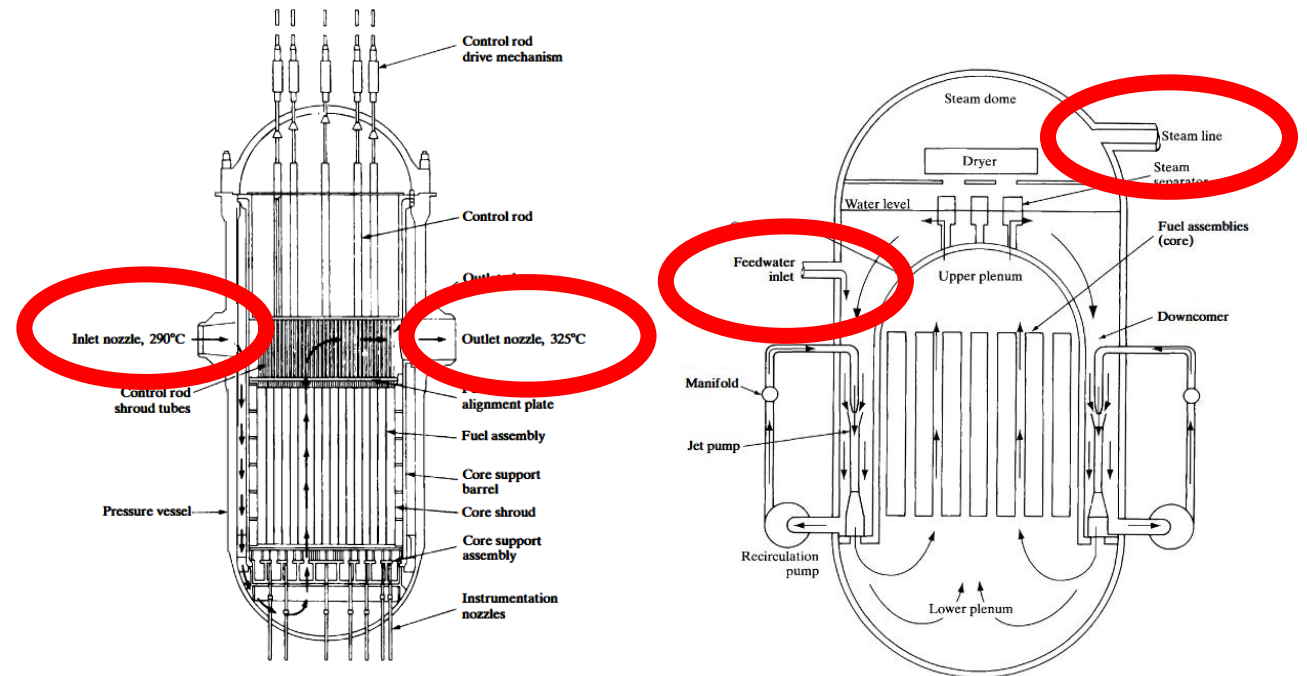
Control Rods

- Inserted into the core to control the rate of fission
 - Inserted – Fission rate slows
 - Removed – Fission rate rises
- Poison-doped stainless steel
- In an emergency “SCRAM”, control rods are all fully inserted to shut down the reactor



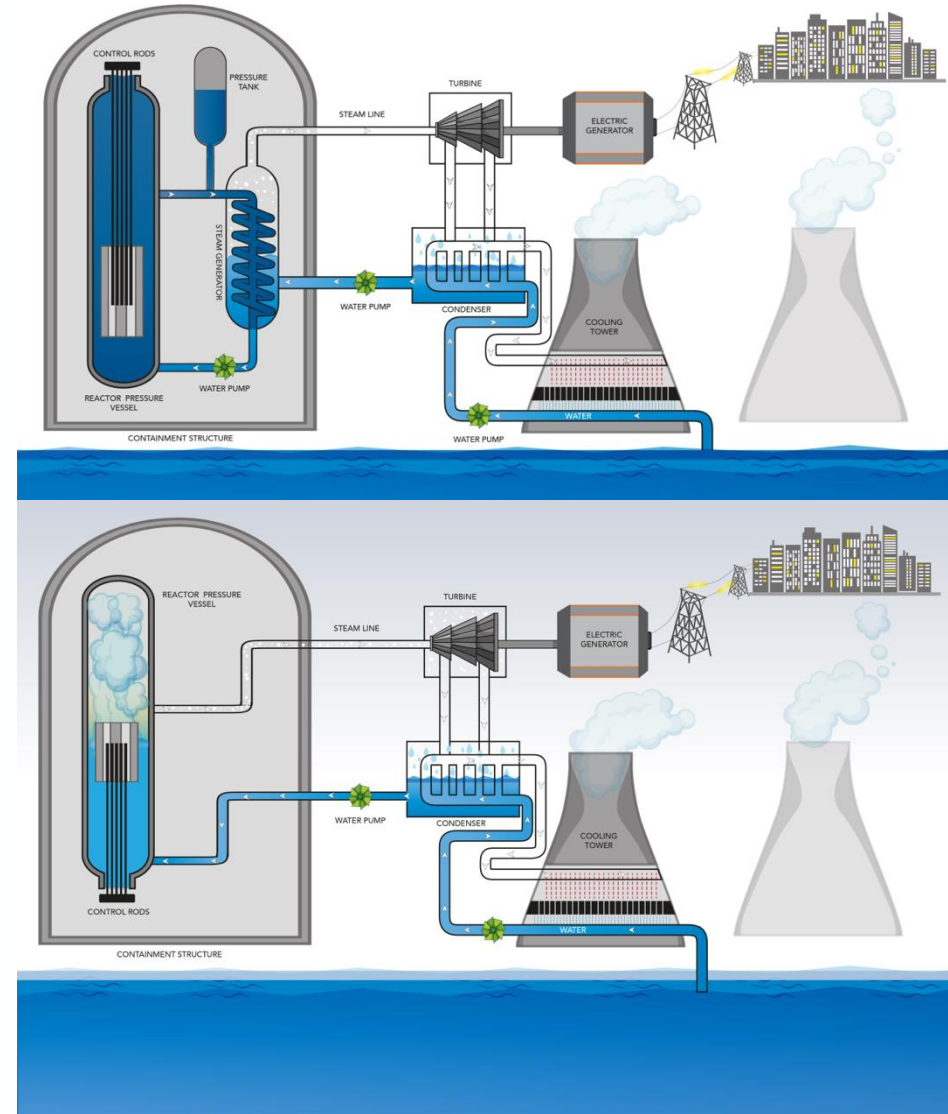
Steam/Water Inlet/Outlet

- Inlet – Coolant coming from turbines is directed through the core
- Outlet – Coolant from the core is passed to the turbines as either hot water or steam
- This circulation is the driving principle for how nuclear reactors generate power



Outside the core

- Turbines – Steam spins the turbines to generate power
- Condenser – Transforms the steam back into water
- Cooling tower – Releases heat into the atmosphere
- Recirculation pump – Pumps the coolant back into the reactor vessel



Pressurized Water Reactors

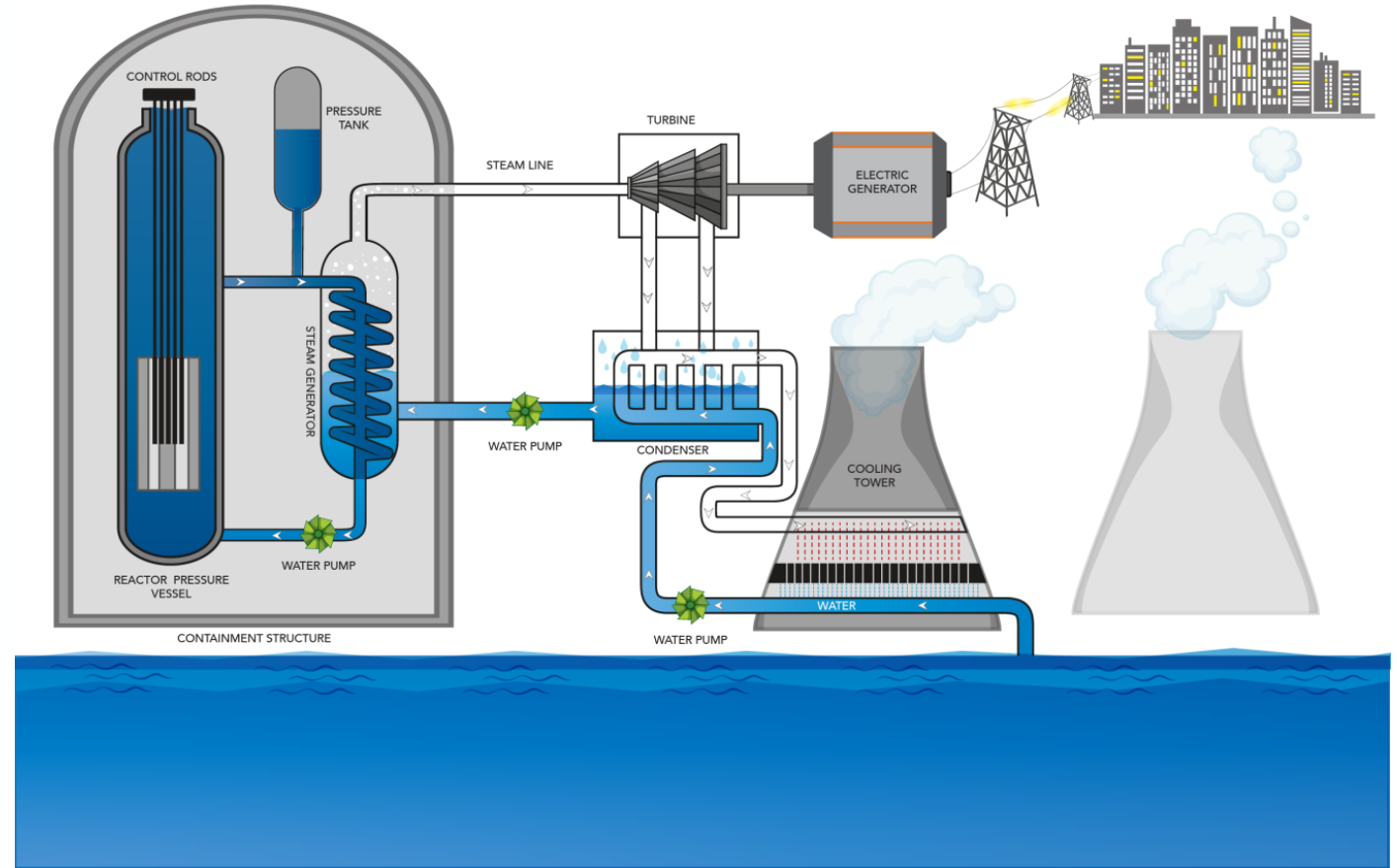
Fuel: Enriched UO_2

Coolant: Light Water (H_2O)

Moderator: Light Water (H_2O)

Key characteristics

- Pressurized to 150atm to allow for higher water temperatures without creating steam
- Top inserting control rods
- Two separate loops of coolant



Boiling Water Reactors

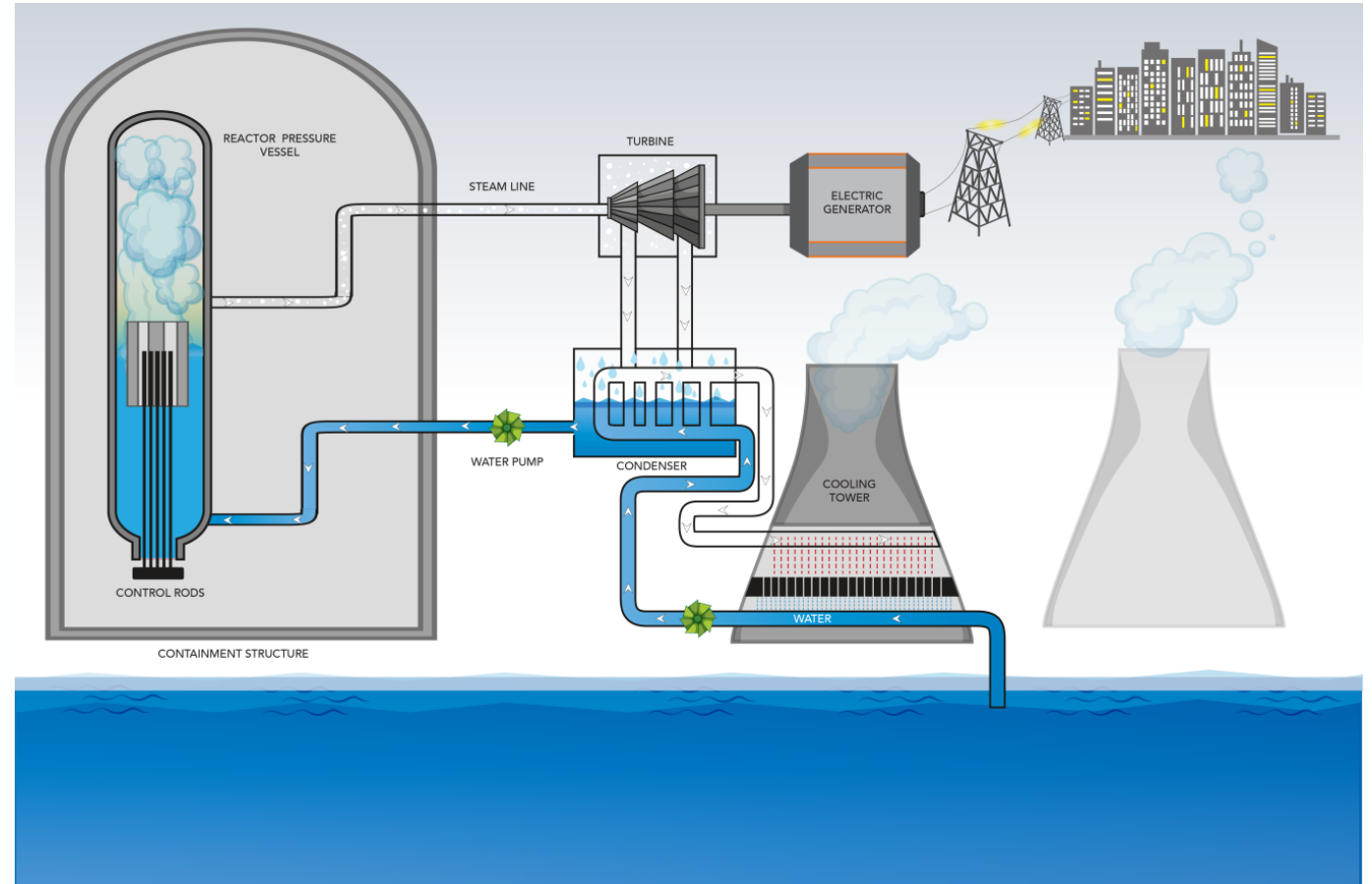
Fuel: Enriched UO_2

Coolant: Light Water (H_2O)

Moderator: Light Water (H_2O)

Key characteristics

- Steam created within the reactor vessel, which is pumped directly to turbine
- Bottom inserting control rods
- One loops of coolant



Other Reactor Types

Heavy Water Reactors

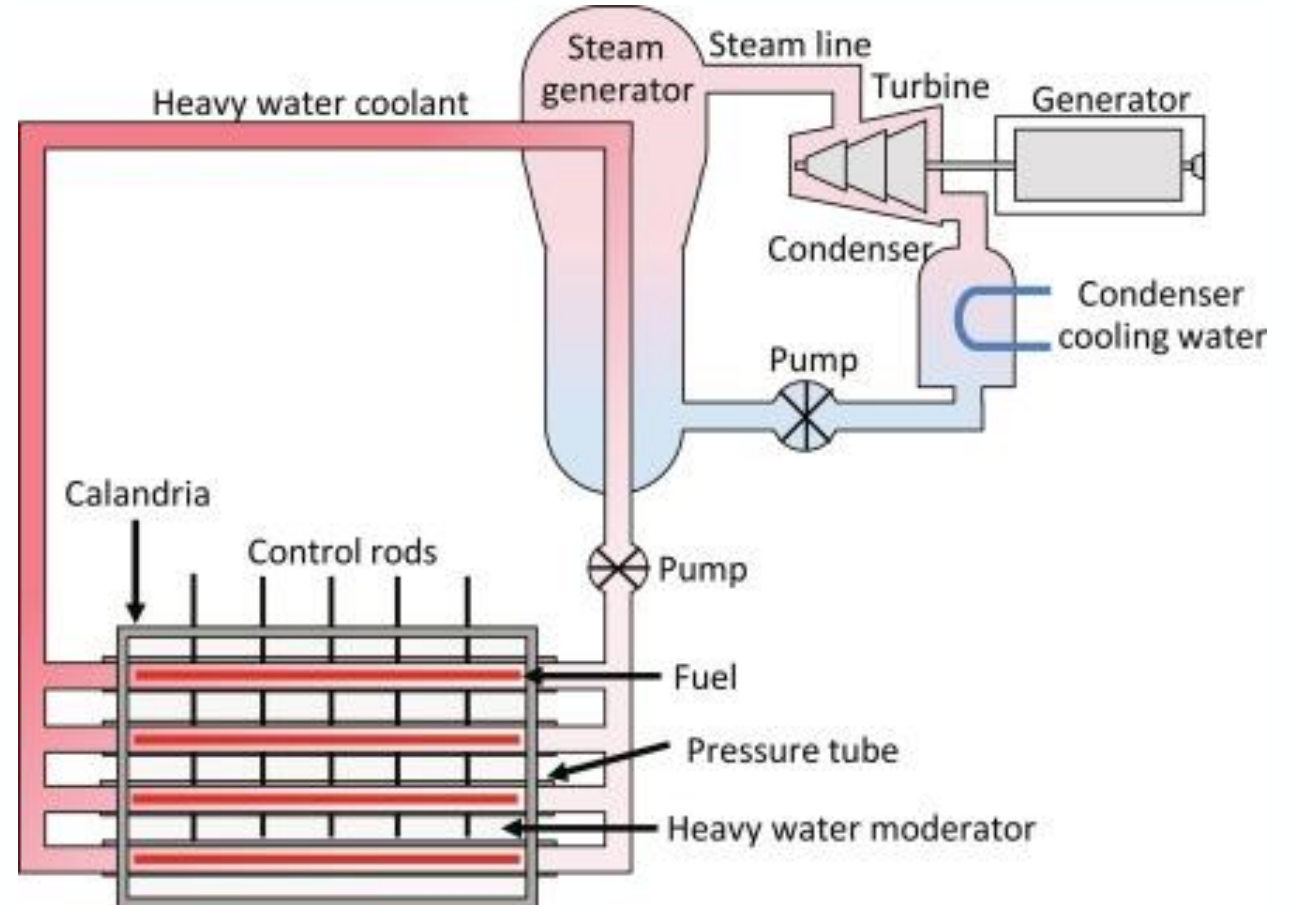
Fuel: Natural Uranium

Coolant: Heavy Water (D_2O)

Moderator: Heavy Water (D_2O)

Key characteristics

- D_2O has lower absorption cross section, but is a worse moderator
- Some designs have on-site refueling without the need to shutdown



Gas Cooled Reactors

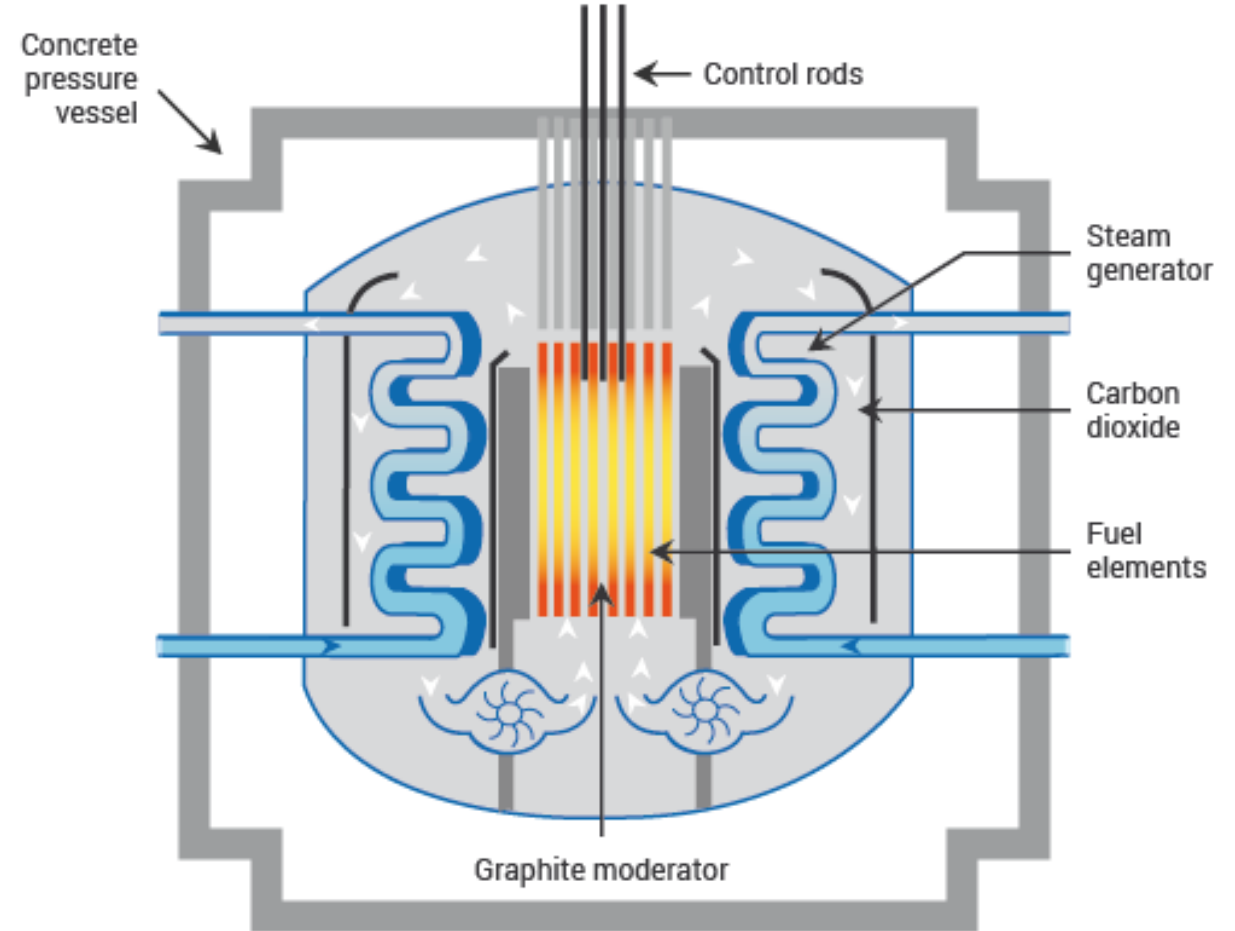
Fuel: TRISO fuel, etc.

Coolant: CO_2 or helium gas

Moderator: Graphite

Key characteristics

- High thermal conductivity, low absorption cross section, and is chemically inert
- High core temperature (900K) can be used for process heat
- TRISO fuel has better heat conductance and protection against corrosion



Liquid Metal Reactors

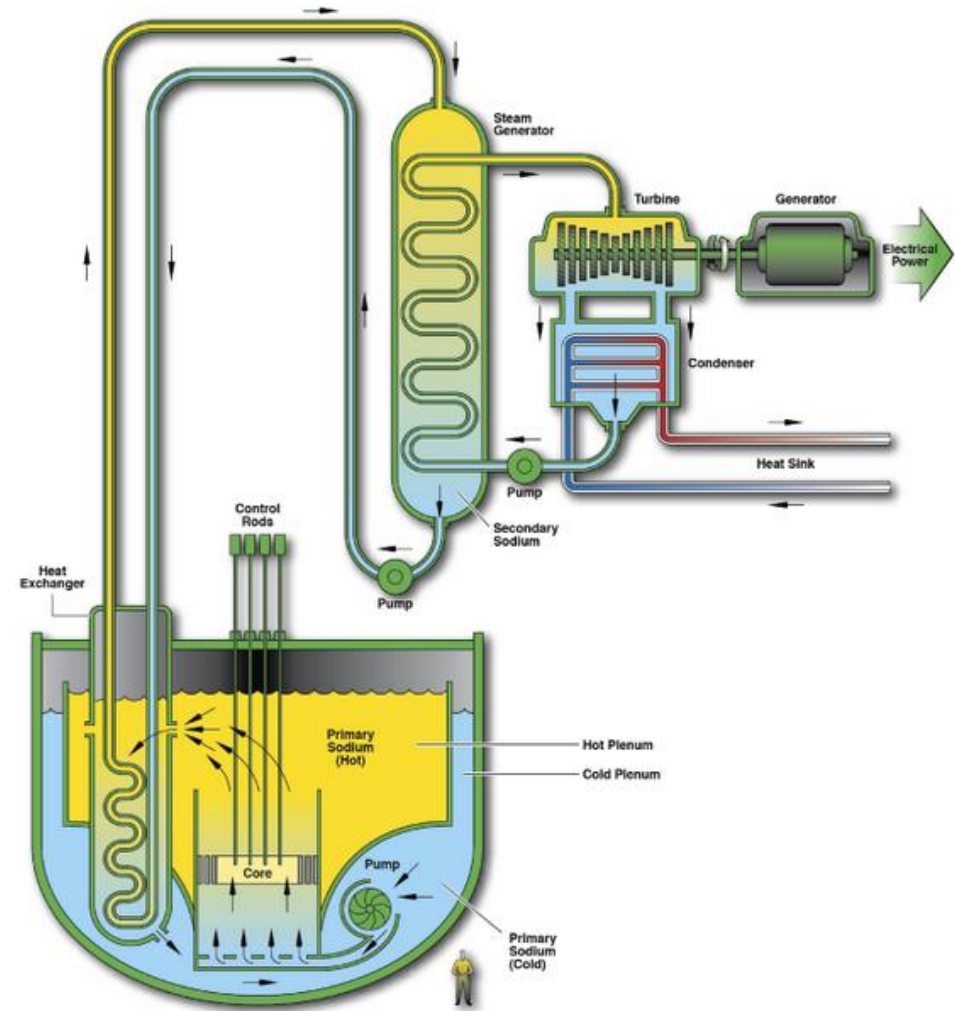
Fuel: MOX (Uranium/Plutonium Mix)

Coolant: Liquid metal (Sodium)

Moderator: None!

Key characteristics

- Long thermal response time
- Operates at near atmospheric pressure
- Fast spectrum means “closing the fuel cycle”



Molten Salt Reactors

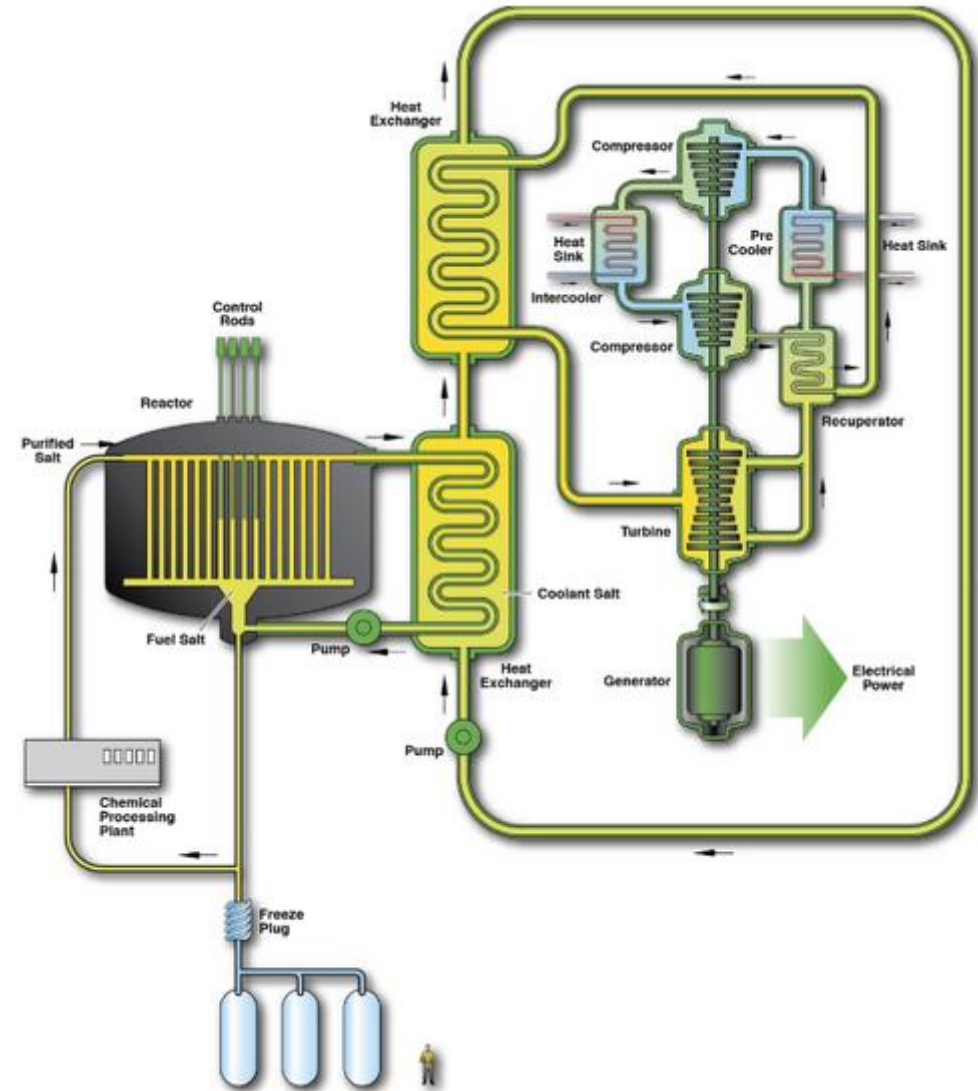
Fuel: Molten metal fuel

Coolant: Molten fluorides or chlorides

Moderator: None!

Key characteristics

- Refueling while operating
- Higher temperature without pressurization
- Fast spectrum means “closing the fuel cycle”



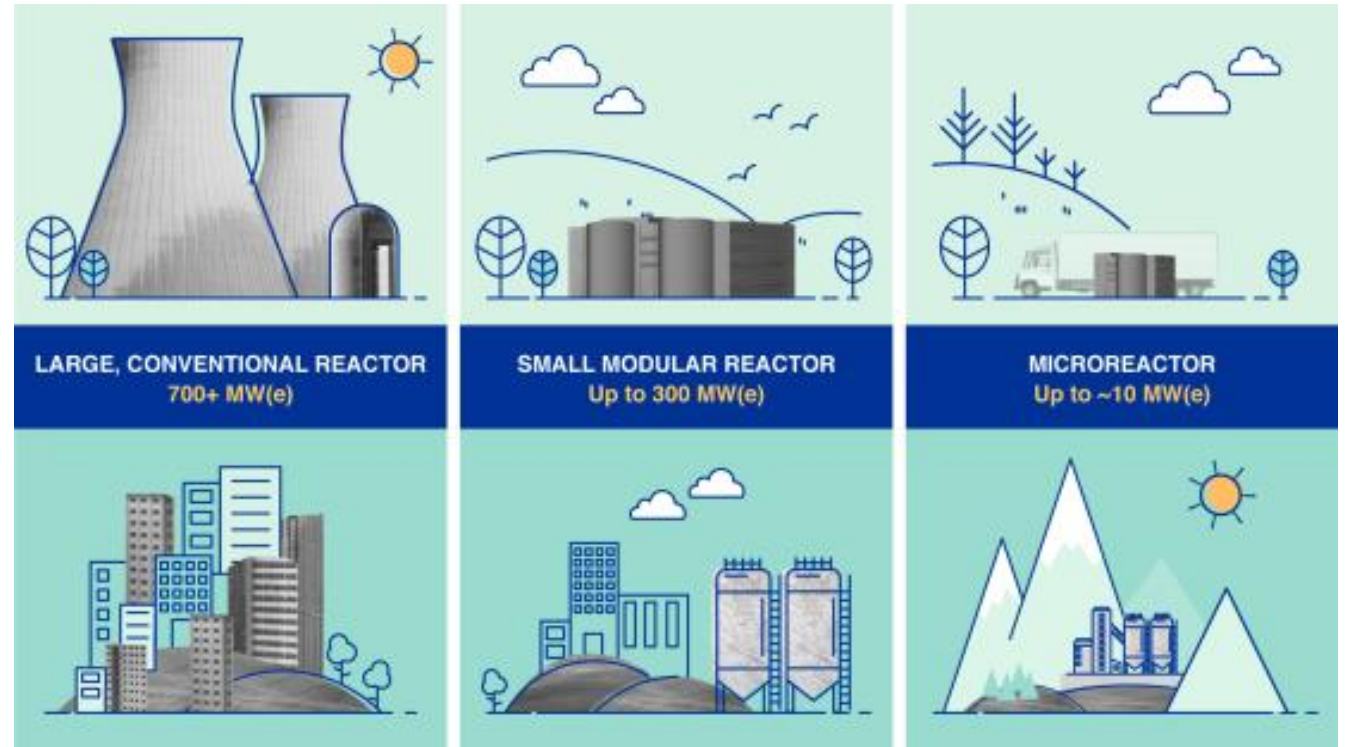
Small Modular Reactors

Small Modular Reactors

- Small – Typically only 300 MWe
- Modular – Factory made parts for easier reproducibility

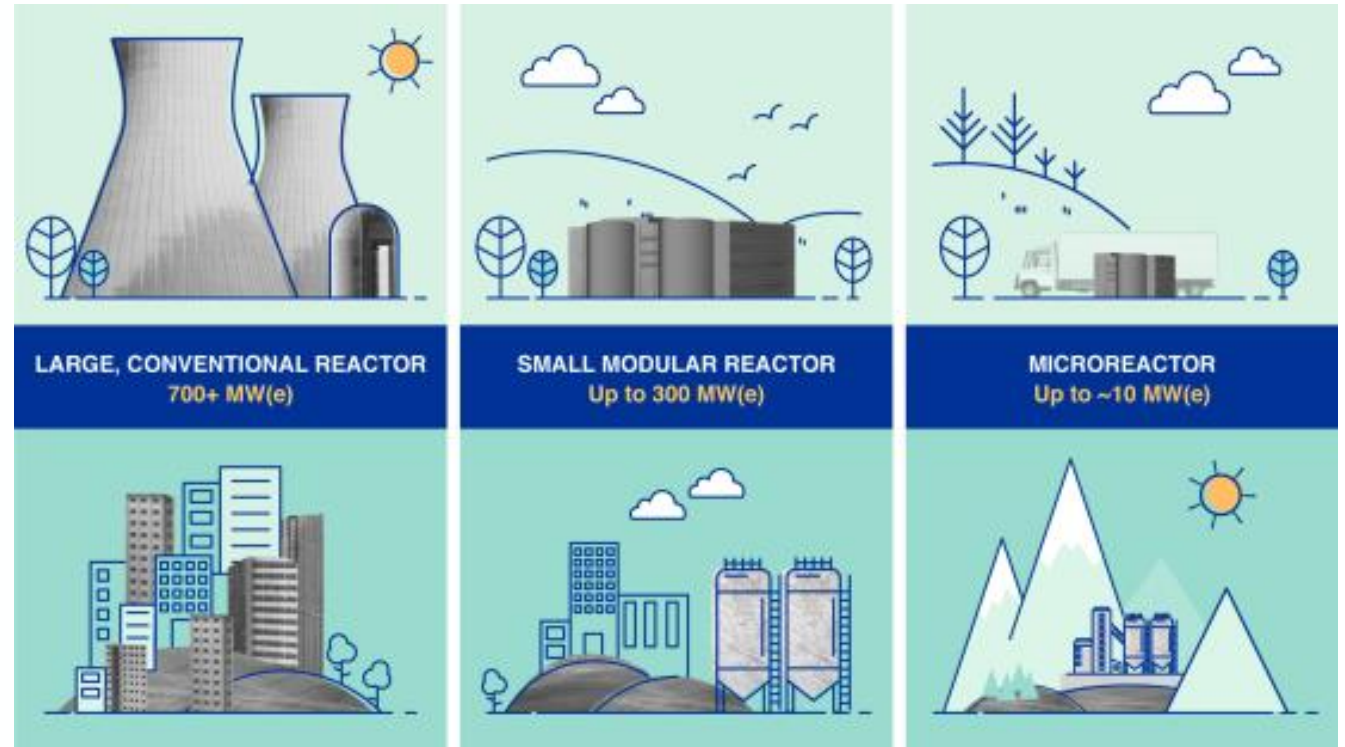
Advantages

- Cited for areas not suitable for large power plants
- Take advantage of existing infrastructure
- Smaller design allows for simpler, safer systems



Microreactors

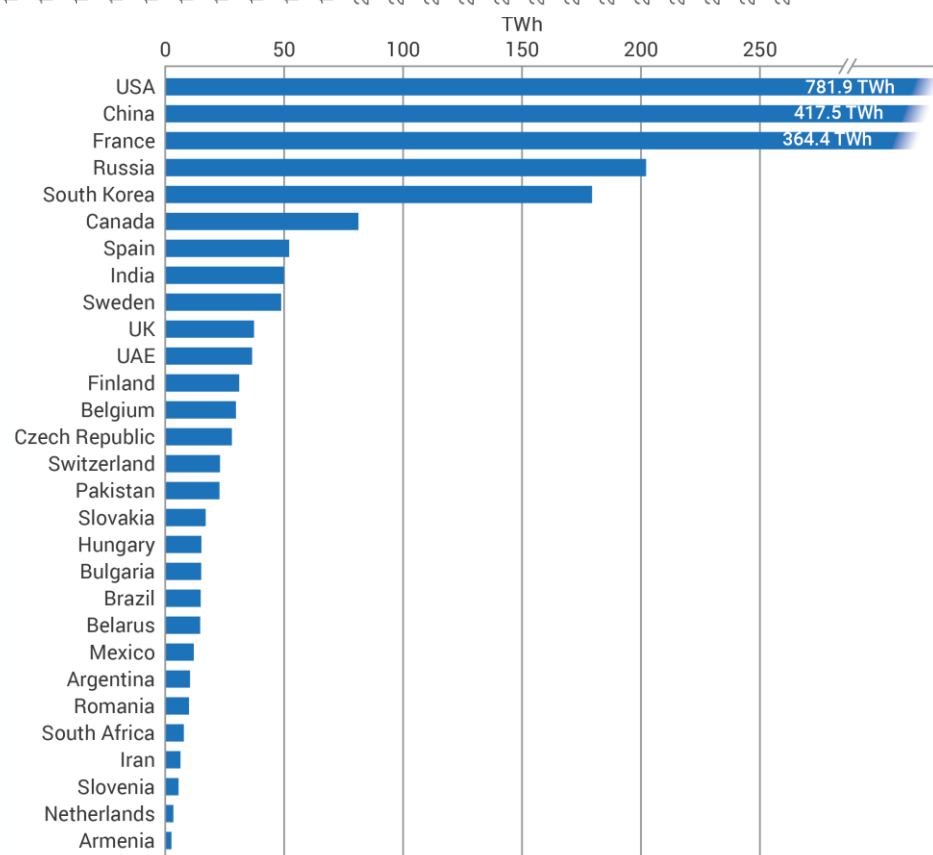
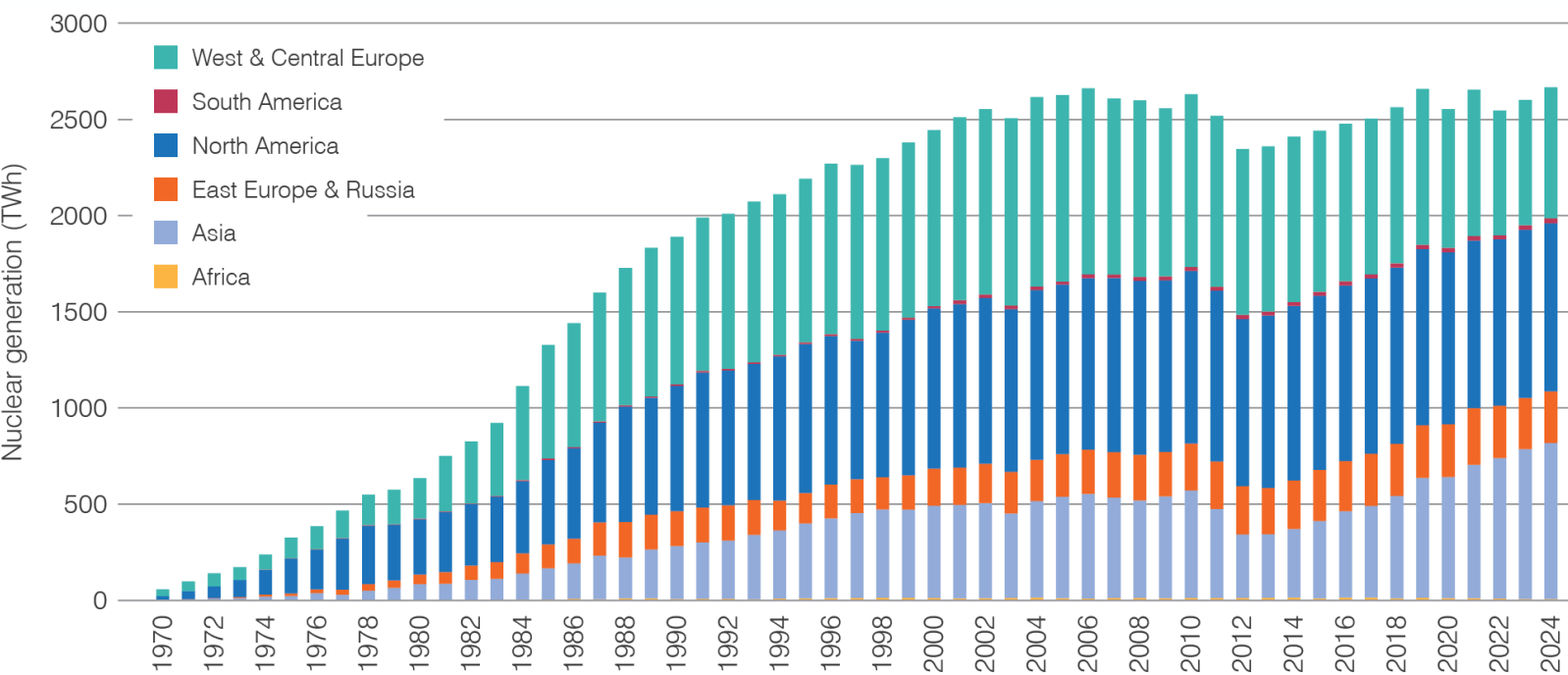
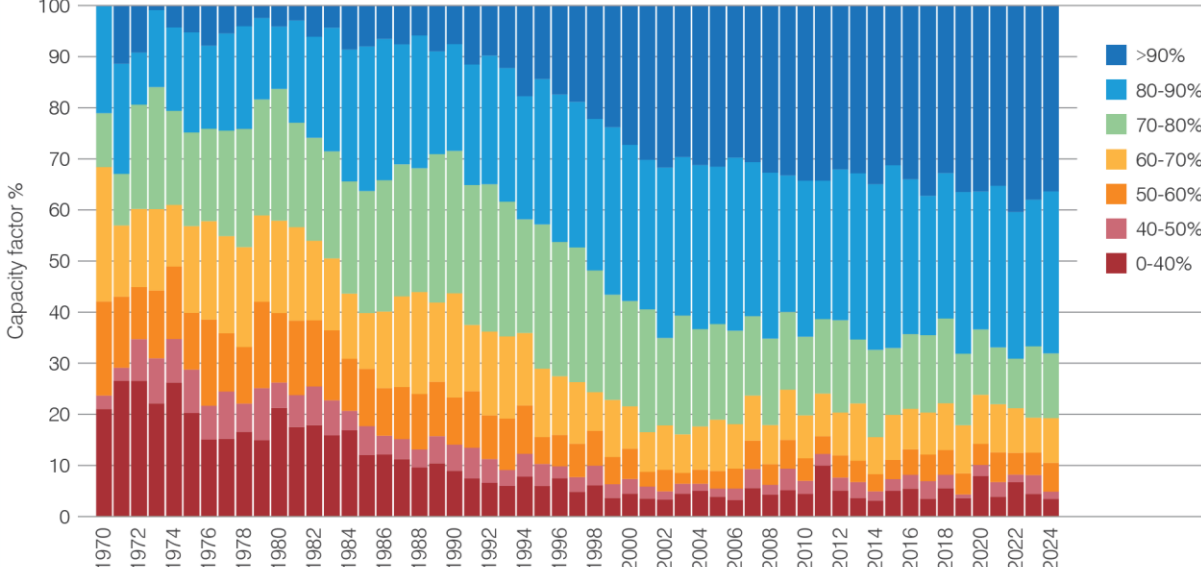
- Microreactors
 - Micro – Typically only 10 MWe
- Advantages
 - Very small carbon footprint
 - Can serve as backup power supply
 - Can be built in rural areas where larger facilities are not economically viable



Summary and Conclusion

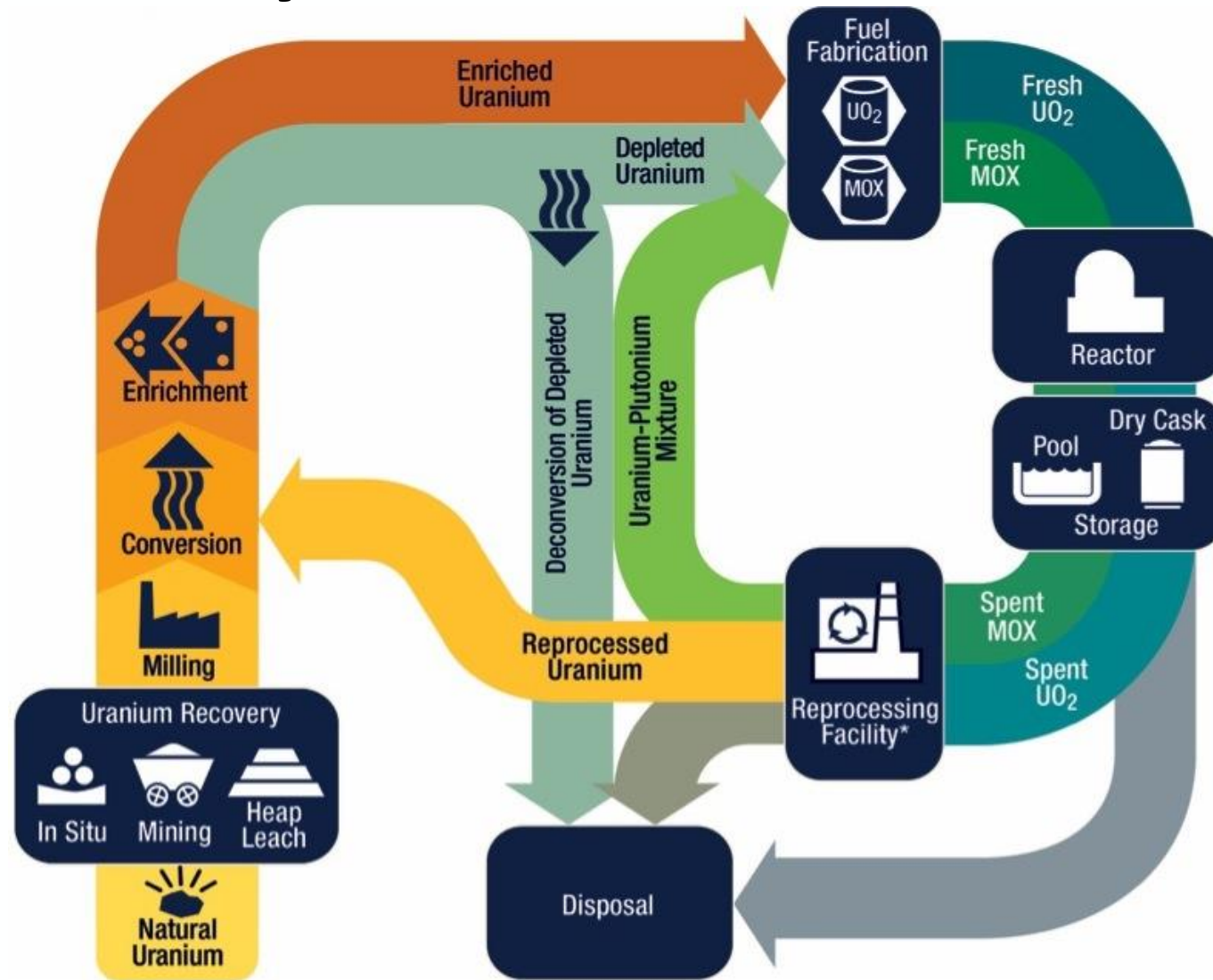
- Nuclear reactions can be used to release the energy holding together the nucleus
- A reactor is controlled through neutrons
 - Fission produces neutrons
 - Scattering brings them down to the thermal range
 - Absorption allows us to control the reaction rate
- Each fission that occurs produces heat, which in standard LWR designs, is used to boil water to steam, which spins turbines, which generates power
- While the US only has LWR designs, other countries utilize a large variety of different reactor types, with more being developed every year

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurized water reactor (PWR)	USA, France, Japan, Russia, China, South Korea	313	302.4	enriched UO ₂	water	water
Boiling water reactor (BWR)	USA, Japan, Sweden	60	61.0	enriched UO ₂	water	water
Pressurized heavy water reactor (PHWR)	Canada, India	47	24.5	natural UO ₂	heavy water	heavy water
Advanced gas-cooled reactor (AGR)	UK	8	4.7	natural U (metal), enriched UO ₂	CO ₂	graphite
Light water graphite reactor (LWGR)	Russia	7	6.5	enriched UO ₂	water	graphite
Fast neutron reactor (FNR)	Russia	2	1.4	PuO ₂ and UO ₂	liquid sodium	none
High temperature gas-cooled reactor (HTGR)	China	1	0.2	enriched UO	helium	graphite



The Nuclear Fuel Cycle

Stages of the Fuel Cycle



Natural Uranium

- The average concentration of uranium in the Earth's crust is 2.7 parts per million
 - About as common as tin or tungsten, significantly more common than precious metals like gold and silver
- Natural uranium consists of 3 different isotopes

Property	U-234	U-235	U-238
Abundance	0.0054%	0.72%	99.274%
Half-Life	250,500 yr	703 million yr	4.468 billion yr
Specific Activity	0.168 Ci/g	2.16E-6 Ci/g	3.35E-7 Ci/g
Thermal Fission Cross Section	0.077 b	585.2 b	N/A
Decay Mode	α (4.858 MeV)	α (4.679 MeV)	α (4.270 MeV)

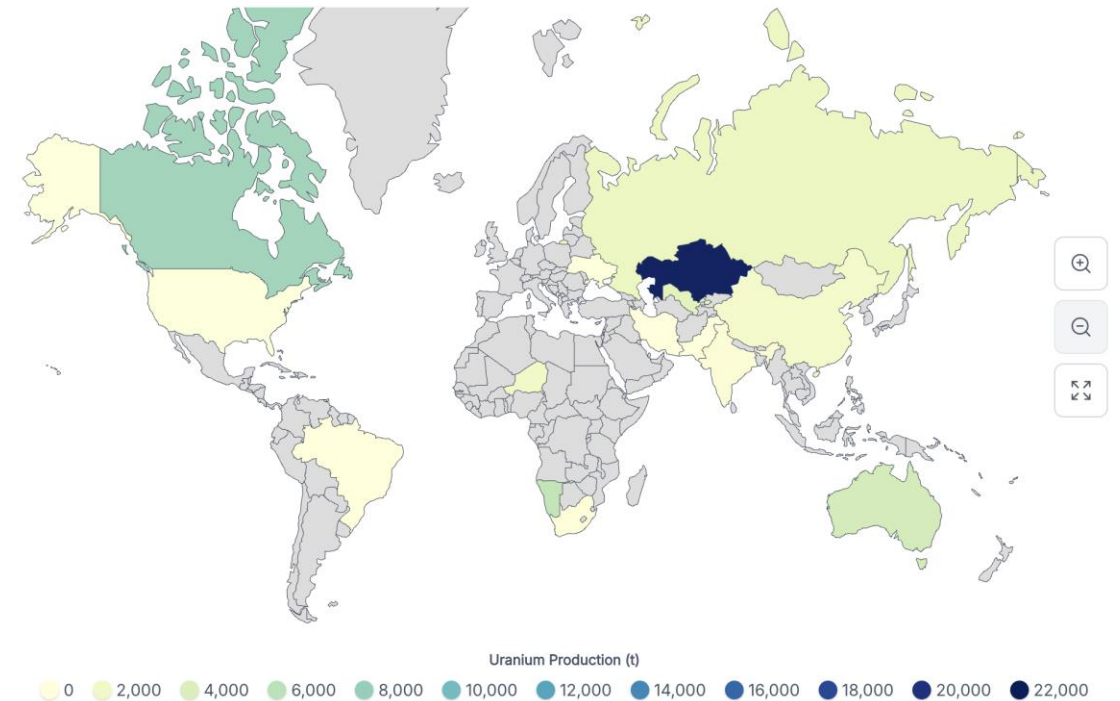


Uranium Recovery

- Uranium can be recovered through several different methods
 - Open pit mining – Rock is blasted and excavated out of large pit in the Earth
 - Underground mining – Ore is extracted from deep underground tunnels and shafts
 - In situ recovery (ISR) – Large injection and extraction wells are drilled deep into a uranium-rich aquifer, and a chemical solution is injected. The solution dissolves uranium out of the rock, and it is then pumped out
 - Heap leach – Ore is physically mined and crushed, but the uranium is collected using the same solution as in ISR, almost like a slow drip coffee machine



Image source: https://en.wikipedia.org/wiki/Uranium_ore#/media/File:Uranium_ore_square.jpg



Milling

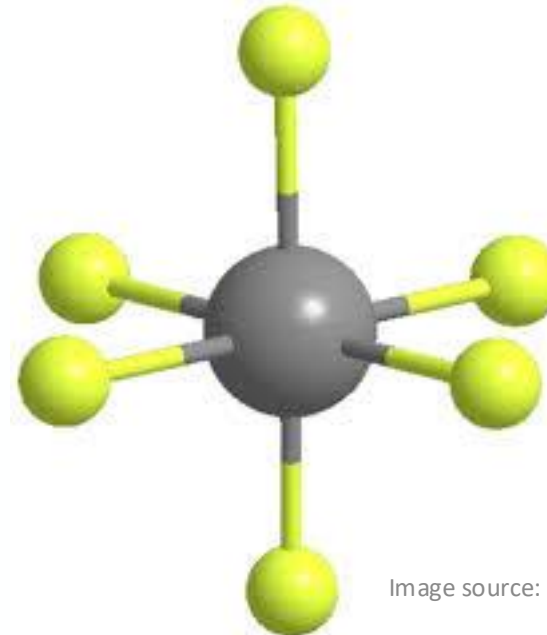


- Milling is the purification and concentration process where uranium ore is produced into U_3O_8
- Uranium ore from mines must be crushed, grinded, and then leached in tanks into a chemical solution and heap leach already does this
- The uranium is then separated from undissolved solids which become the tails of the process
- After the uranium is isolated, ammonia or hydrogen peroxide is added to transform the uranium to a solid precipitate
- The precipitate is dried and roasted to convert the solution into U_3O_8 (yellowcake)



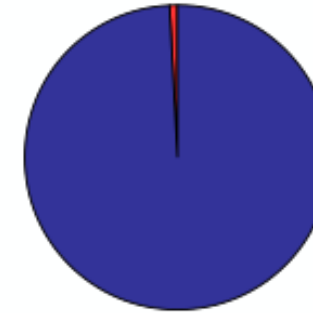
Conversion

- Yellowcake is further refined for chemical purity
- Yellowcake is converted into UF_6 , since it must be in gas form for enrichment
 - Fluorine only has one isotope, meaning differences in isotopic weights of only uranium is present in UF_6
 - UF_6 exists as a gas at convenient temperatures for operations
- Once the gas has been produced, it is shipped to enrichment facilities

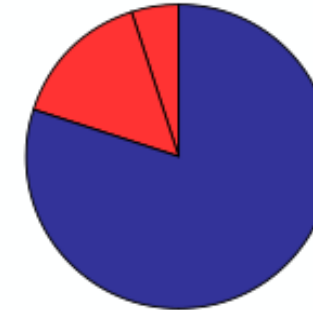


Enrichment

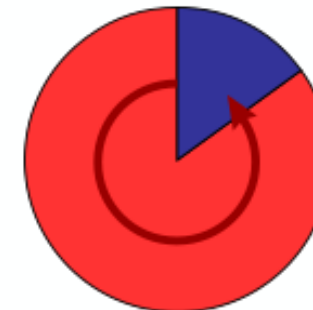
- Enrichment is the process of increasing the proportion of U-235 in fuel
- Many reactor designs require enriched fuel to achieve criticality
- Chemical separation techniques do not work on isotopes of the same element, as they behave identical chemically
- Enrichment takes advantage of the fact that U-235 is *slightly* less massive than U-238
- There are 3 major classifications for enriched uranium
 - Low Enriched Uranium (LEU) 0.72-5%
 - High-Assay Low Enriched Uranium (HALEU) 5-20%
 - High Enriched Uranium (HEU) >20%
- Commercial powerplants operate on 3-5% enrichment
- Enrichment facilities are rigorously monitored, regulated, and inspected by the IAEA



Natural uranium (NU)
>99.2% U-238
≤0.72% U-235



Low-enriched uranium (LEU)
(reactor grade)
<20% U-235
(typically 3-5% U-235)



Highly enriched uranium (HEU)
(weapons grade)
20-85% U-235
(≥85% U-235)

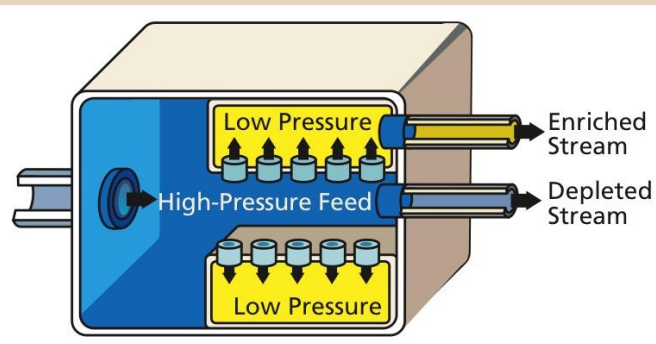


Enrichment Methods

Past

Gaseous Diffusion

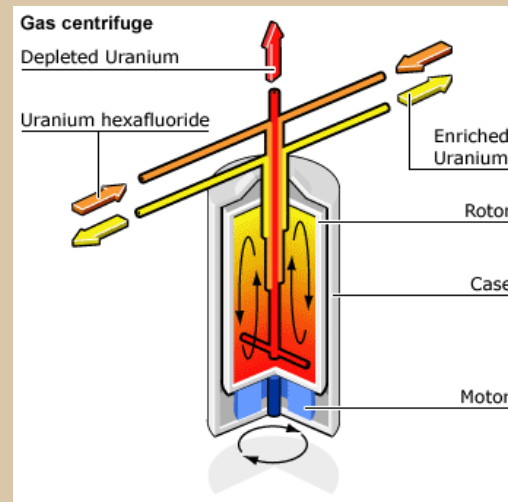
Invented during the Manhattan project and used until 2013. UF_6 is forced through a porous membrane, where the lighter U-235 diffuses faster. UF_6 is enriched after several passes.



Present

Gas Centrifuge

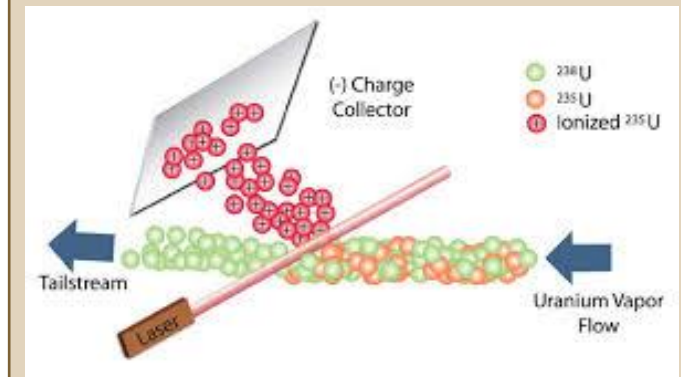
Current process used for enrichment in the US. UF_6 is fed into a cylinder which spins rapidly. Heavier U-238 is pushed to the outside due to higher angular momentum. Inner tube feeds into next centrifuge. Enrichment is completed after several passes.



Future

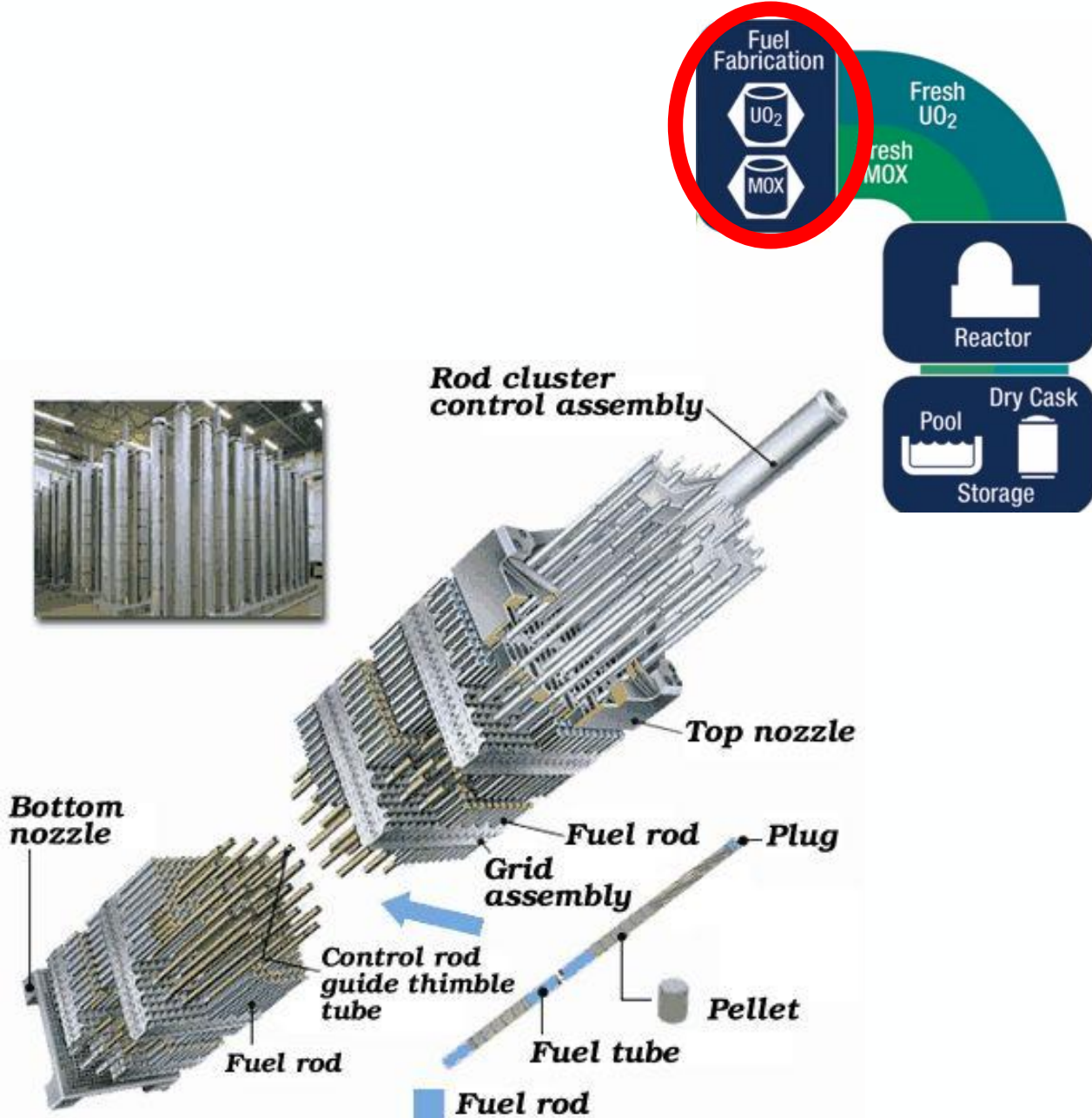
Laser Separation

Currently under development. Precisely tuned lasers can photo-ionize specific isotopes, chemically altering them, making separation possible.



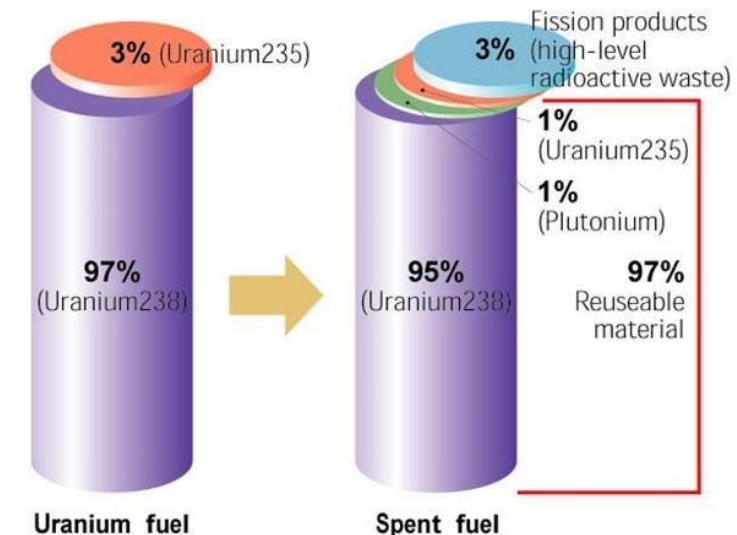
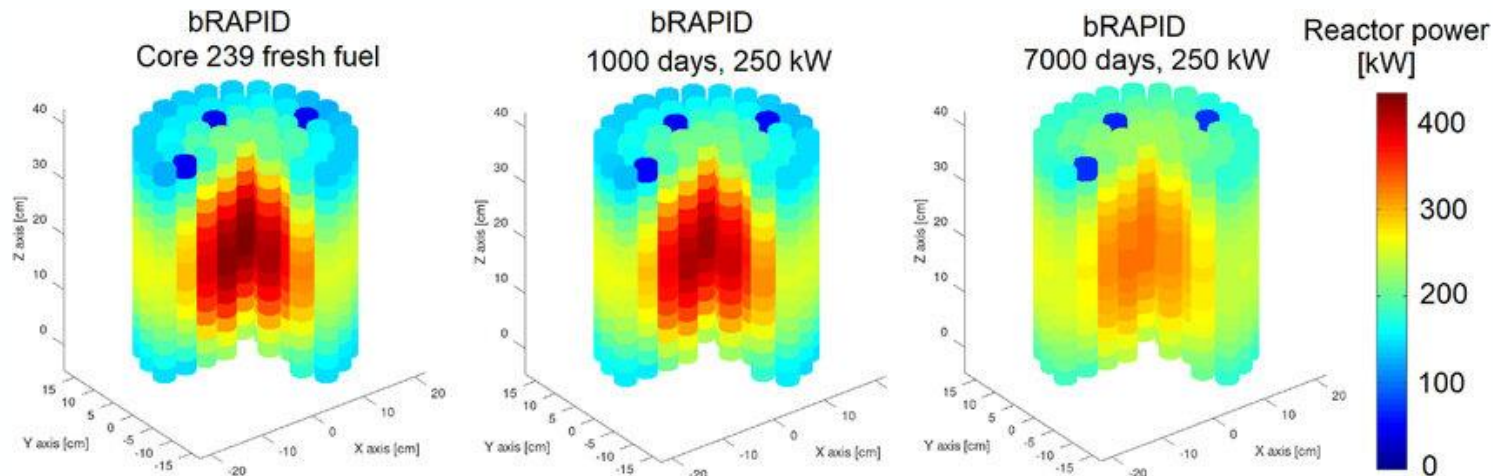
Fuel Fabrication

- Enriched UF_6 is converted into UO_2 powder which is manufactured into small pellets (1 cm diameter)
- Pellets are loaded into a fuel rod made of zircaloy (zirconium alloy) cladding which is then filled with helium for improved heat transfer
- Fuel rods are assembled into a square array to form a fuel assembly
- A standard 4-loop 1100 Mwe PWR contains 193 fuel assemblies with 264 fuel rods
- Other types of fuels not found in LWRs:
 - CANDU
 - TRISO
 - MOX
 - Metallic Fuel
 - Homogenous Fuel



Fuel Lifetime in Reactor

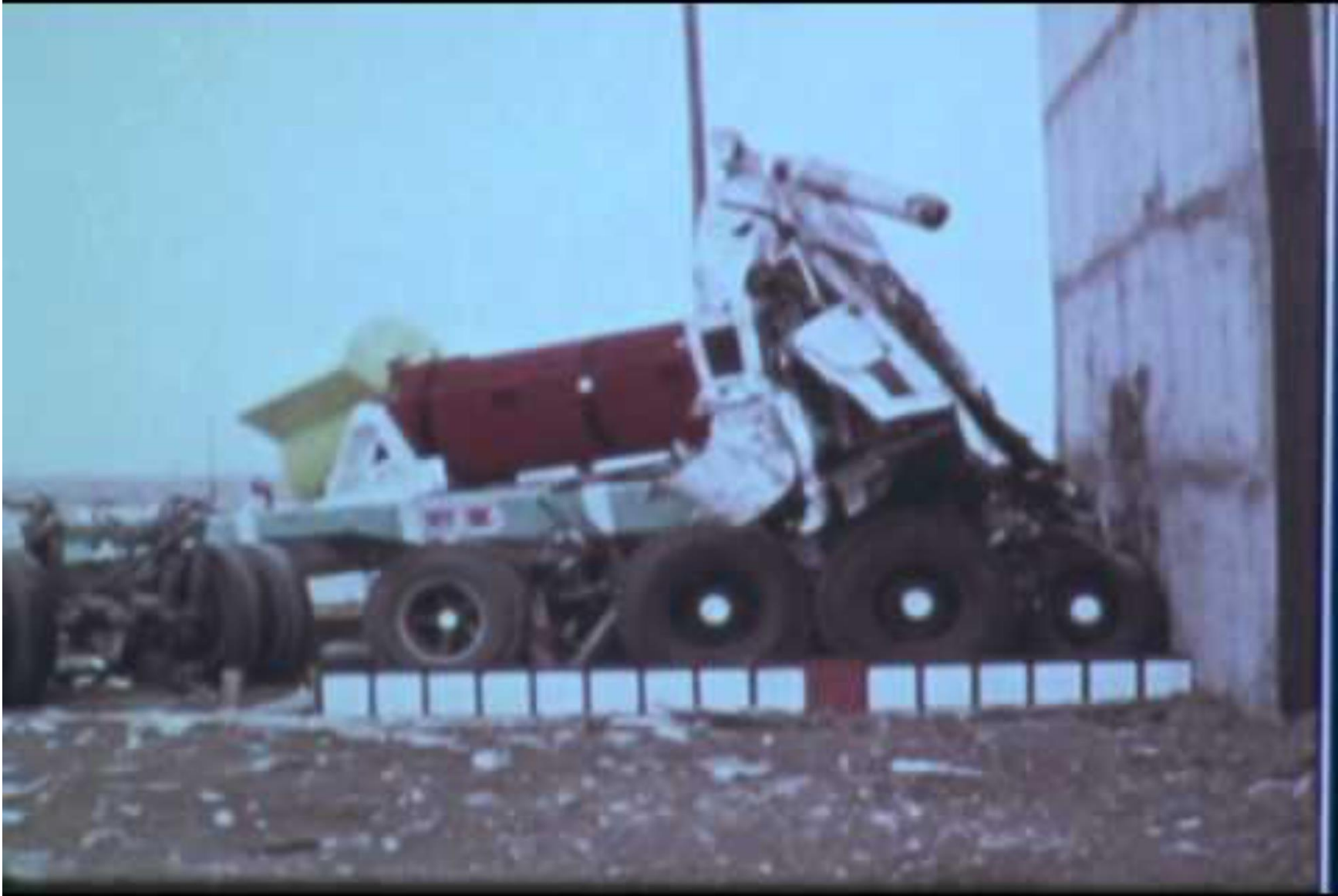
- The entire fuel cycle exists to provide fuel for the reactor during this stage, and deal with the after
- As the U-235 in the fuel continues to undergo fission in a reactor core, the fissile material is depleted and turned into fission products
- Additionally, U-238 gets activated and eventually decays into Pu-239 which is fissile and also contributes to the power output
- Many reactors operate on 18-24 month cycles. Each cycle, only a portion (typically 1/3 or 1/4) of the fuel assemblies are swapped out, the rest are shuffled for more even burnup



Spent Fuel Storage

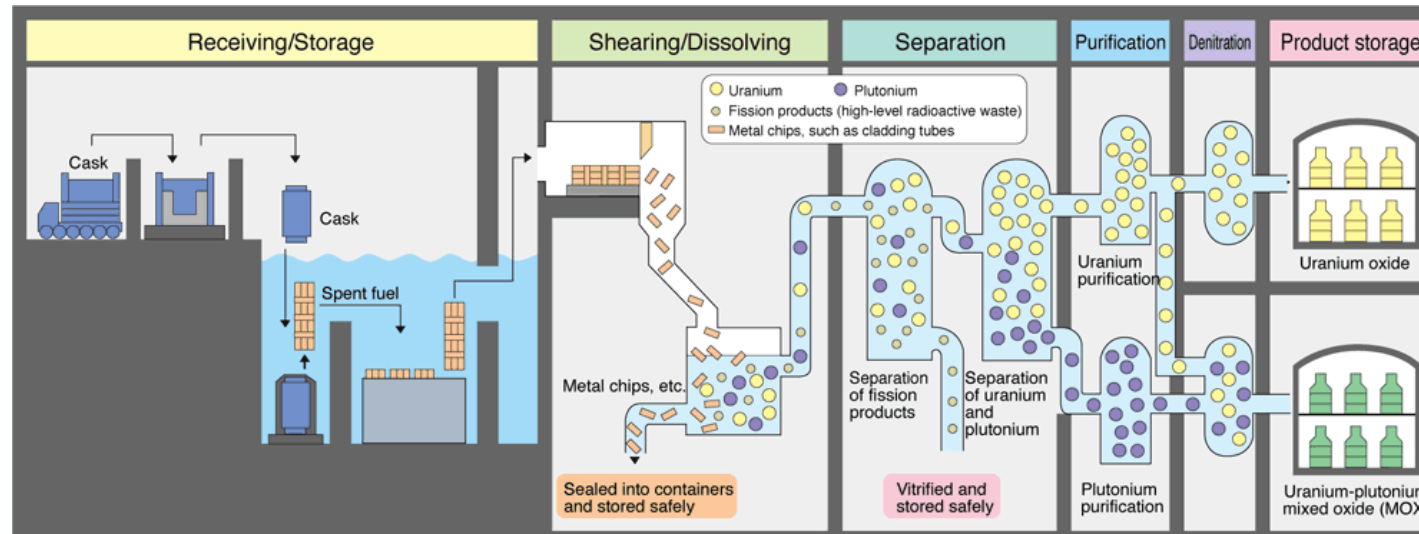
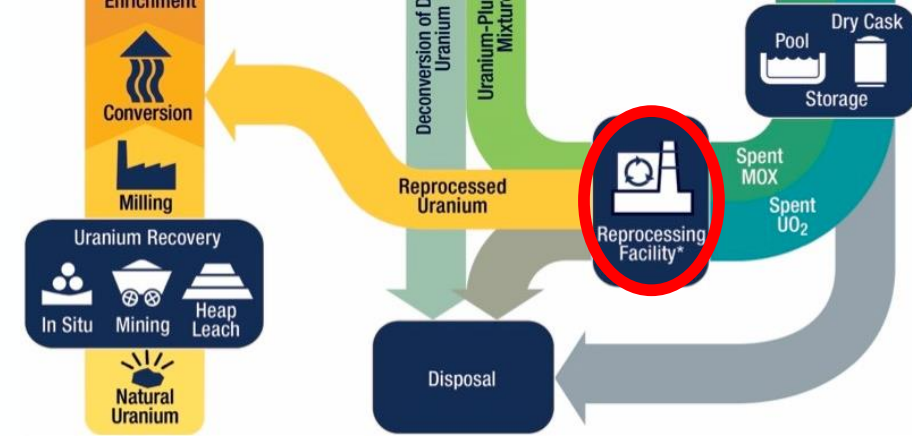
- Spent fuel is still producing significant heat once it is removed
- It must be placed in an onsite pool for 5-10 years to cool off
- After the pool, spent fuel is moved to onsite dry casks
 - Originally, dry casks were intended as a temporary solution until a permanent repository was built
 - Now, dry casks are the de facto permanent storage system in the US
- A permanent repository was planned for Yucca Mountain in Nevada, but plans halted in 2010 due to political pressure





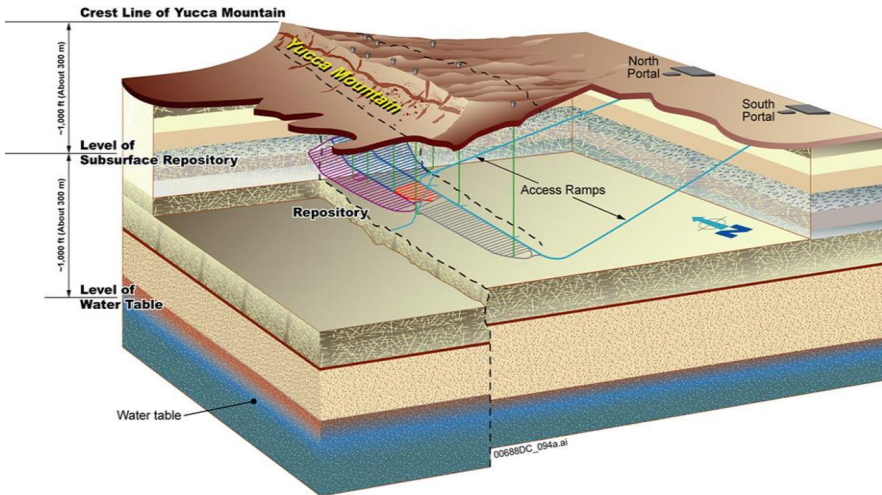
Reprocessing

- Reprocessing is not currently done by the US due to nonproliferation
- Spent fuel is reprocessed via the PUREX process
 - Spent fuel assemblies are dissolved, and the plutonium, uranium, and fission products are chemically separated
- PuO_2 is blended with UO_2 at MOX fuel facilities
- Reprocessed uranium (RepU) can undergo enrichment and be recycled back into a reactor
- The fission products form high level liquid waste (HLLW), which can be vitrified into a stable glass form for long-term storage



Disposal

- 1982 Nuclear Waste Policy Act - Established a legal framework for a geological waste repository
 - Nuclear utilities paid \$1/MWh into project until 2014, totaling ~\$30 billion
- Yucca Mountain in Nevada was chosen as the repository site
- Project lost funding in 2010 due to political pressure
- On site dry casks are now the de-facto permanent storage solution in the US

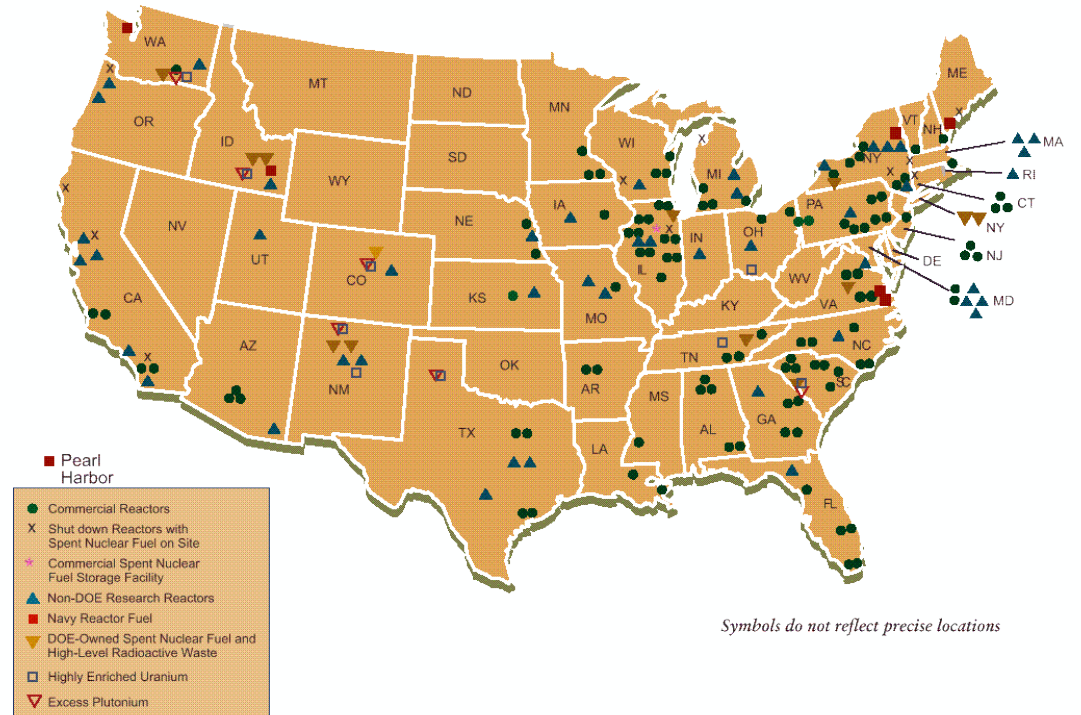


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Image source: <https://longnow.org/ideas/yucca-mountains-future/>



Locations of Spent Nuclear Fuel and High-Level Radioactive Waste Destined for Geologic Disposal



Symbols do not reflect precise locations

Image source: <https://www.yuccamountain.org/map.htm>

Nuclear Waste Misconceptions

- “There is no solution to the nuclear waste problem”
 - Geological repositories and fuel reprocessing are two different methods which are proven effective by other countries
- “Nuclear waste is hazardous for tens of thousands of years”
 - Within 1,000-10,000 years, spent fuel is as radioactive as uranium ore. Other industries produce hazardous chemical waste that will remain hazardous forever (mercury, lead, etc.)
- “Nuclear energy produces too much waste”
 - U.S. commercial reactors have produced only 90,000 metric tons of spent fuel since the 1950’s, enough to fill a football field to a depth of less than 10 yards
 - Coal power plants collectively produce over 100 million metric tons of waste every year
- “It leaks into the earth, water, and atmosphere”
 - Every gram of US commercial spent fuel ever produced is accounted for, tracked, and contained
 - On-site dry casks are engineered to withstand floods, fires, and even plane crashes

Questions?



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