GET1024 / GEC1036 Lecture 13

Nuclear Fuel Cycle & Nuclear Wastes

Nuclear Fuel Cycle

- Front and Back Ends
- Mining & Milling
- Conversion and Enrichment
- Fresh and Spent Fuel

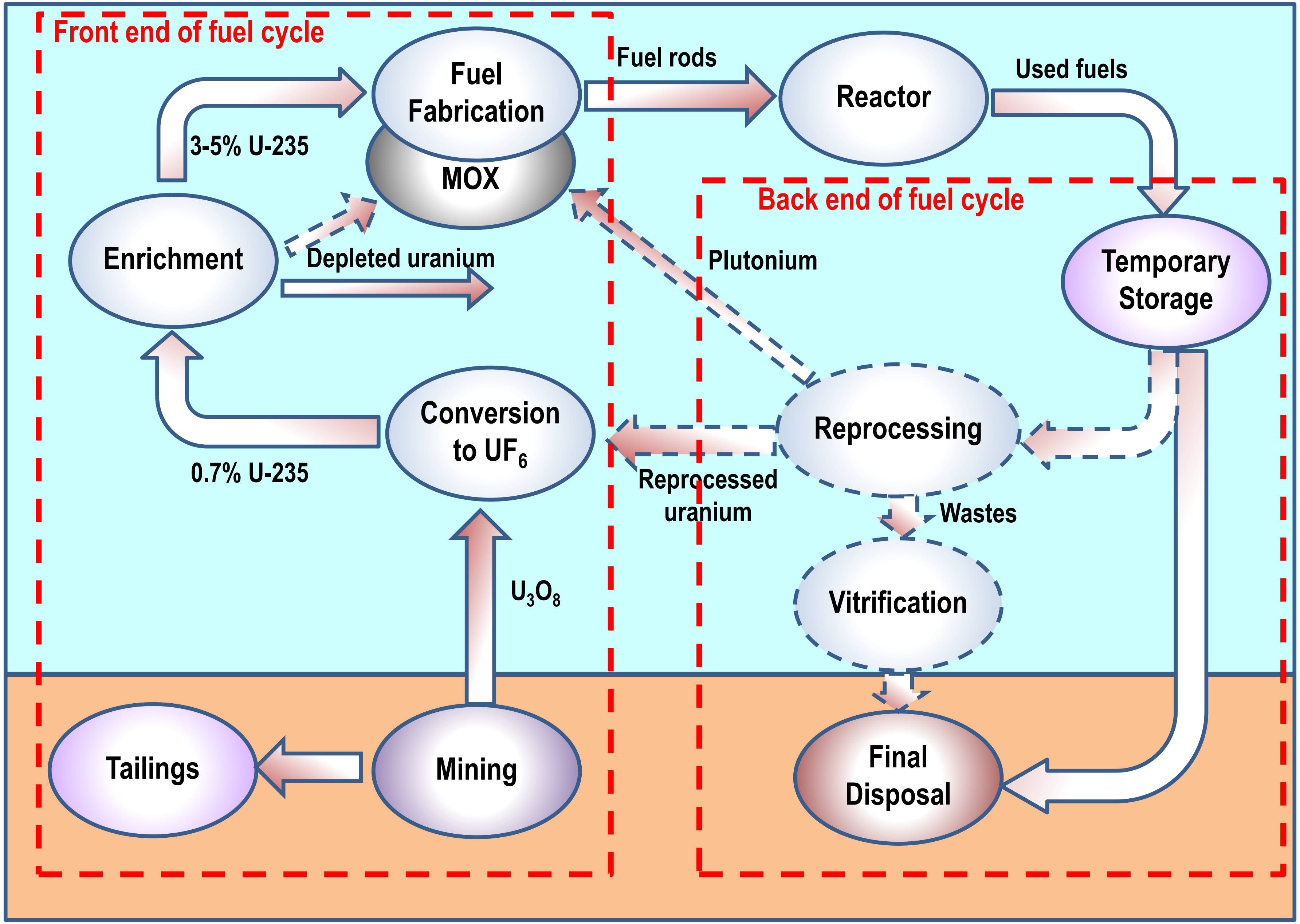
Waste Management

- Spent Fuel Pool and Dry Cask
- Reprocessing & Vitrification
- Deep Geological Repository
- Classification of Wastes
- Opposing Views on Waste
- Waste Disposal

Introductory Remarks

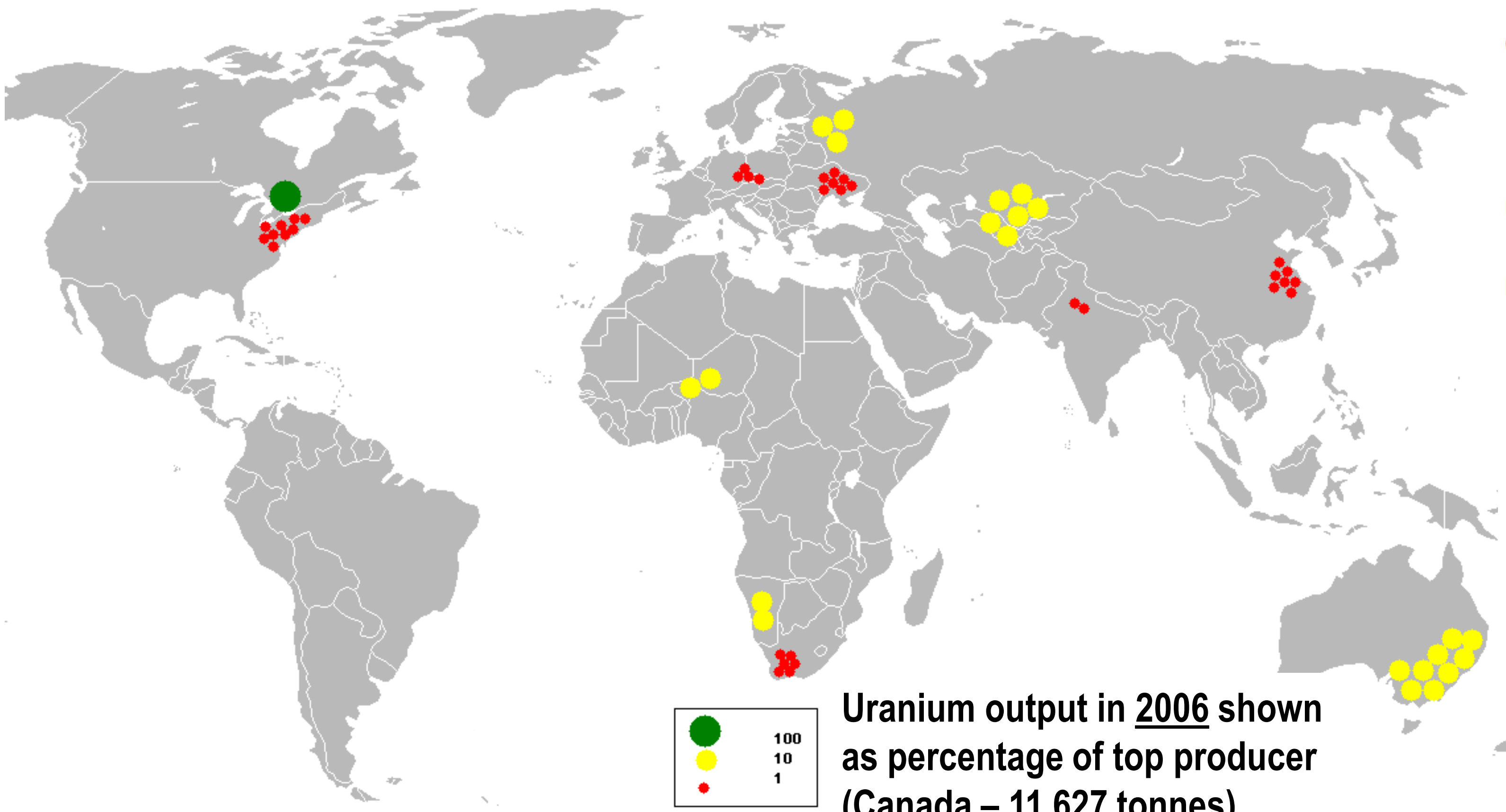
- The risk of ionising radiation exposure for operating NPPs comes not only during accidents but during many stages of the whole process of producing and using the nuclear fuel.
- At the same time, the radioactive products from the fission process have various lengths of half-lives, making spent fuel one of the highest radioactive materials which have to carefully cooled (in the first few years after removal from reactors) and difficult to store.
- Wastes from the whole process, particularly the spent fuels, remain one of the main objections to the use of nuclear power in many countries.
- We will look at the risks from the production of the nuclear fuel and the products after use in this lecture.

Nuclear Fuel Cycle

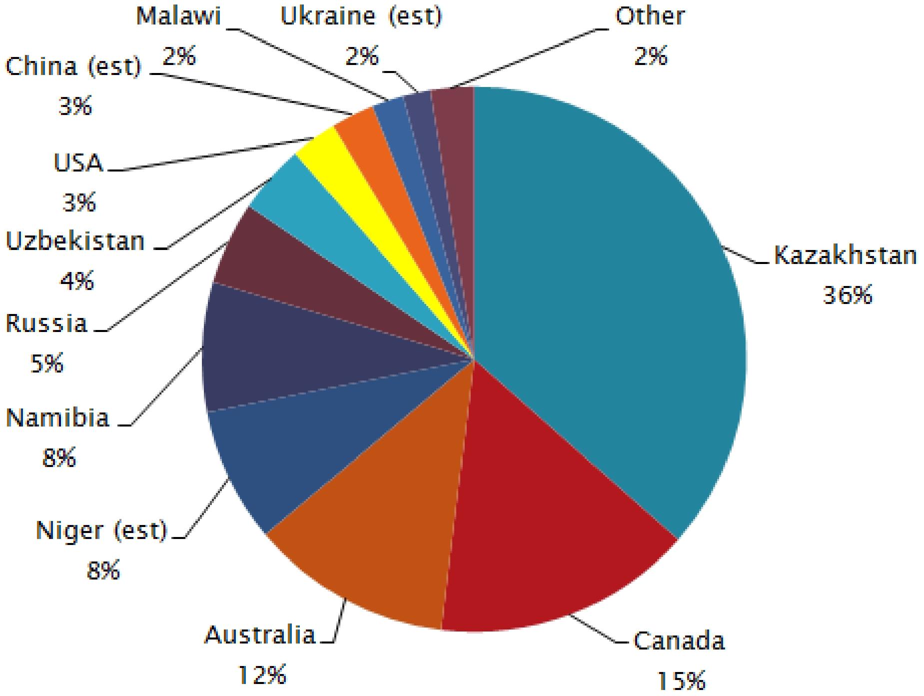


- **Nuclear Fuel Cycle**: the various activities associated with the production of electricity from nuclear
- The cycle starts with the mining of uranium and ends with the disposal of nuclear waste.
- With the reprocessing of used fuel as an option for nuclear energy, the stages form a true cycle.

Uranium Mines in the World



Uranium output in 2006 shown as percentage of top producer (Canada – 11,627 tonnes)



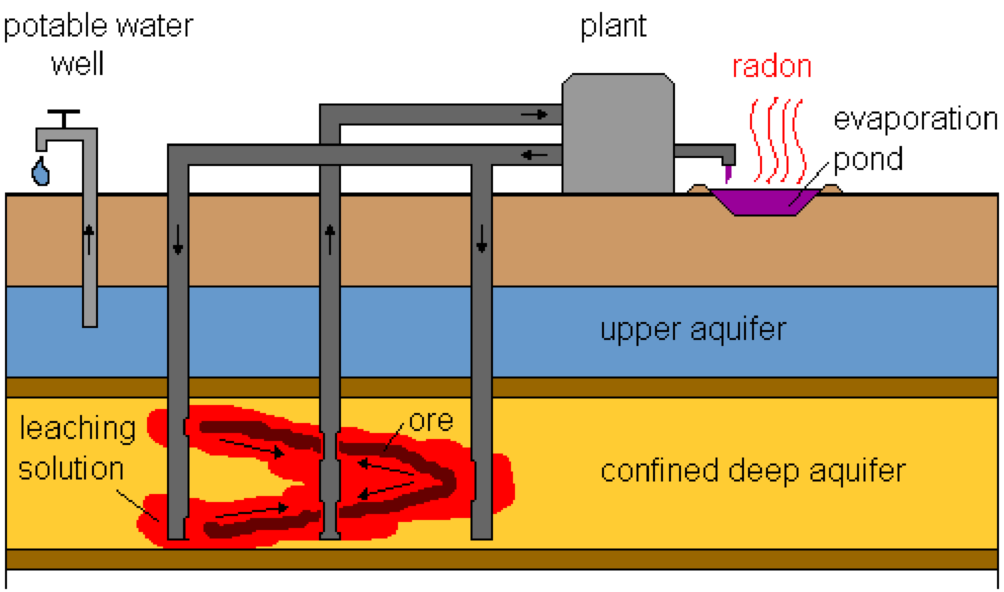
World Uranium Mining Production 2012

Hi-grade uranium ore	> 20,000 ppm
Average-grade uranium ore	1,000 ppm
Granite	4 ppm
Aqueous (Sedimentary) rock	2 ppm
Average in Earth's crust	2.8 ppm
Sea water	0.003 ppm

Uranium is one of the more common elements in Earth's crust (about 500 times more abundant than gold, as common as tin).

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

Uranium Mining Methods



Open Pit Mining

- Ores near surface (< 120 m)
- Large footprint - large amount of soil dug – waste rocks
- Least expansive

Underground Mining

- Ores deeper (up to 600 m)
- Shafts, tunnels (small footprint)
- Health risk is higher from radiation including radon
- More expansive

In Situ Leaching (ISL) Mining

- Acidic / alkaline water pumped in – to separate uranium from soil
- Uranium in solution pumped up
- Little waste rocks
- Contamination of aquifer is possible

Possibility of extraction from seas in future – uranium can last almost indefinitely.

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

Uranium Milling

Uranium Ores containing ~0.2% U_3O_8 & others such as V_2O_5, MoO_3, SeO_2

Milling

1. Crushing
2. Leaching
3. Filtration
4. Precipitation
5. Purification

85% U_3O_8
(200 tons needed for 1 GW_e PWR a year)

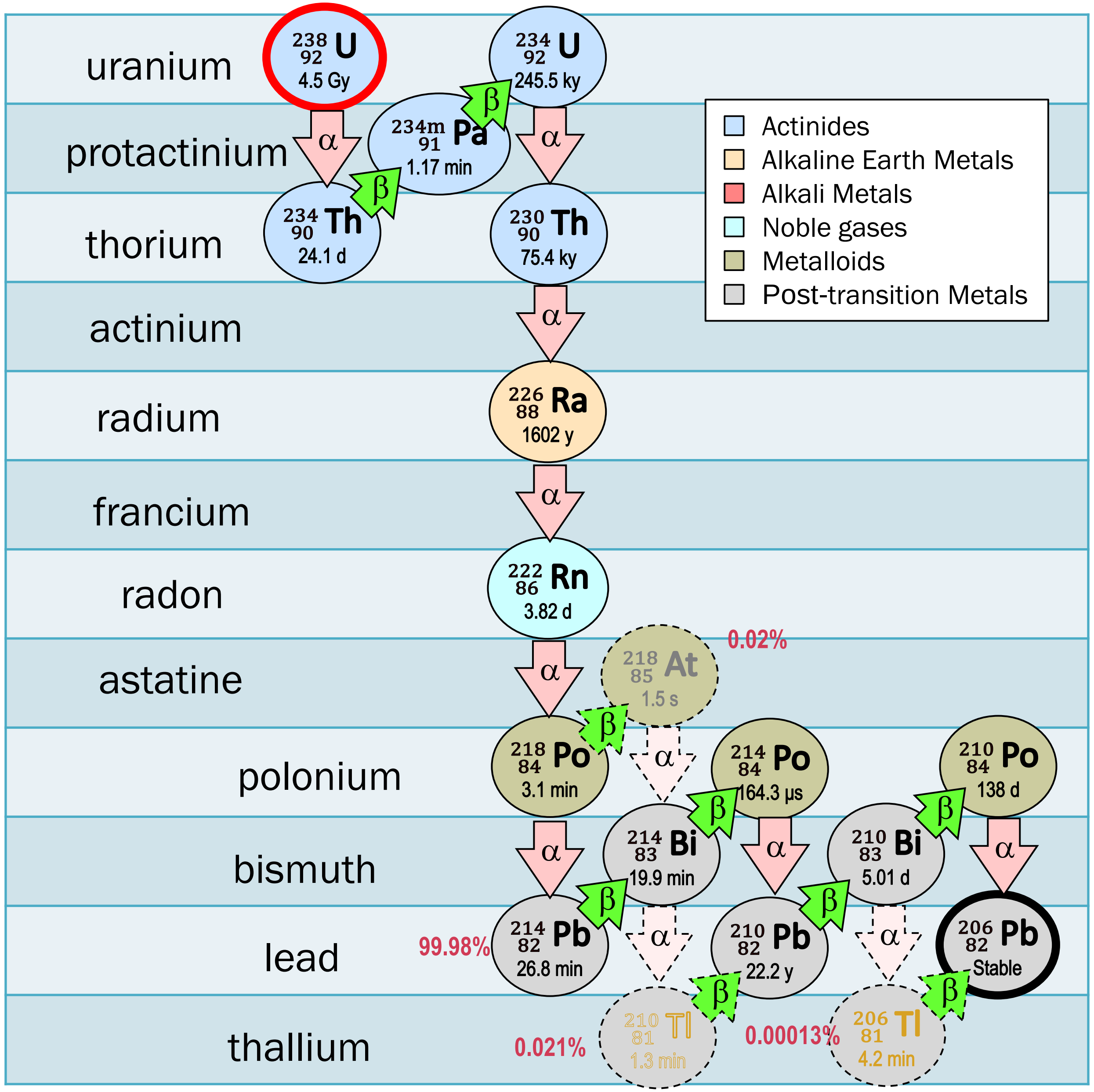
+

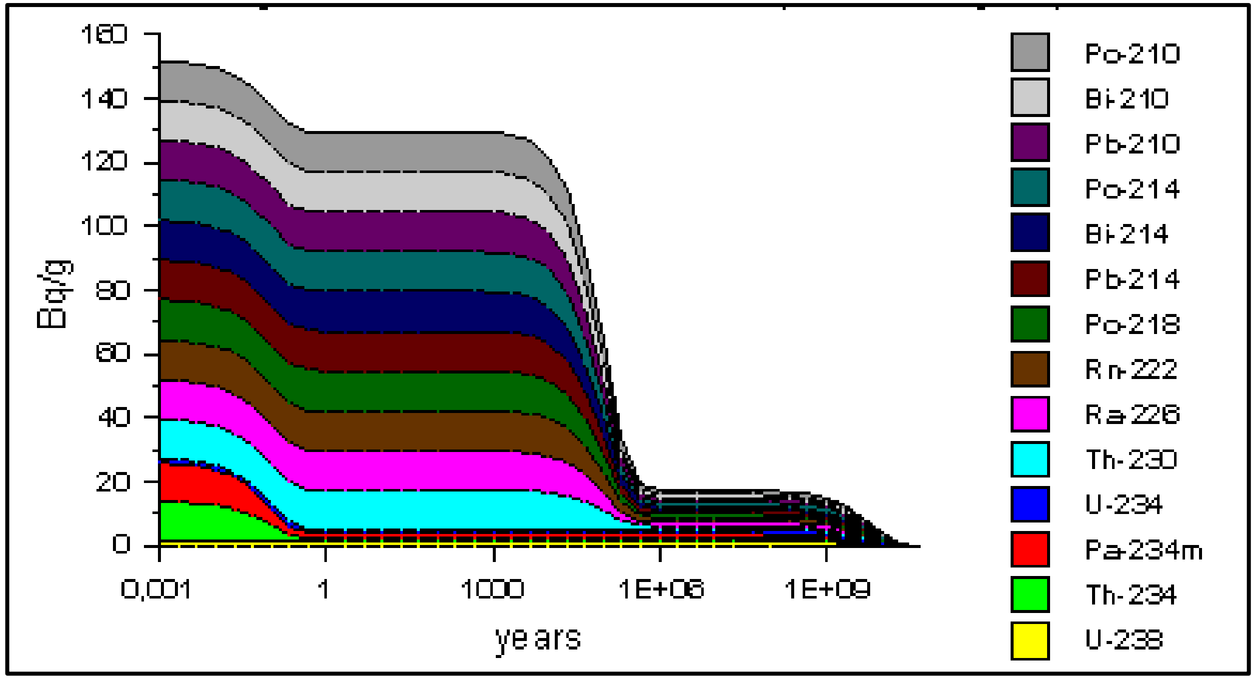
"heavy metal" including molybdenum, vanadium, selenium, iron, lead, arsenic

+

100,000 tons of ore required a year for 1 PWR
$\Rightarrow$ ≈ 100,000 tons of mill tailings generated

Radioactive Isotopes in Uranium Mill Tailings



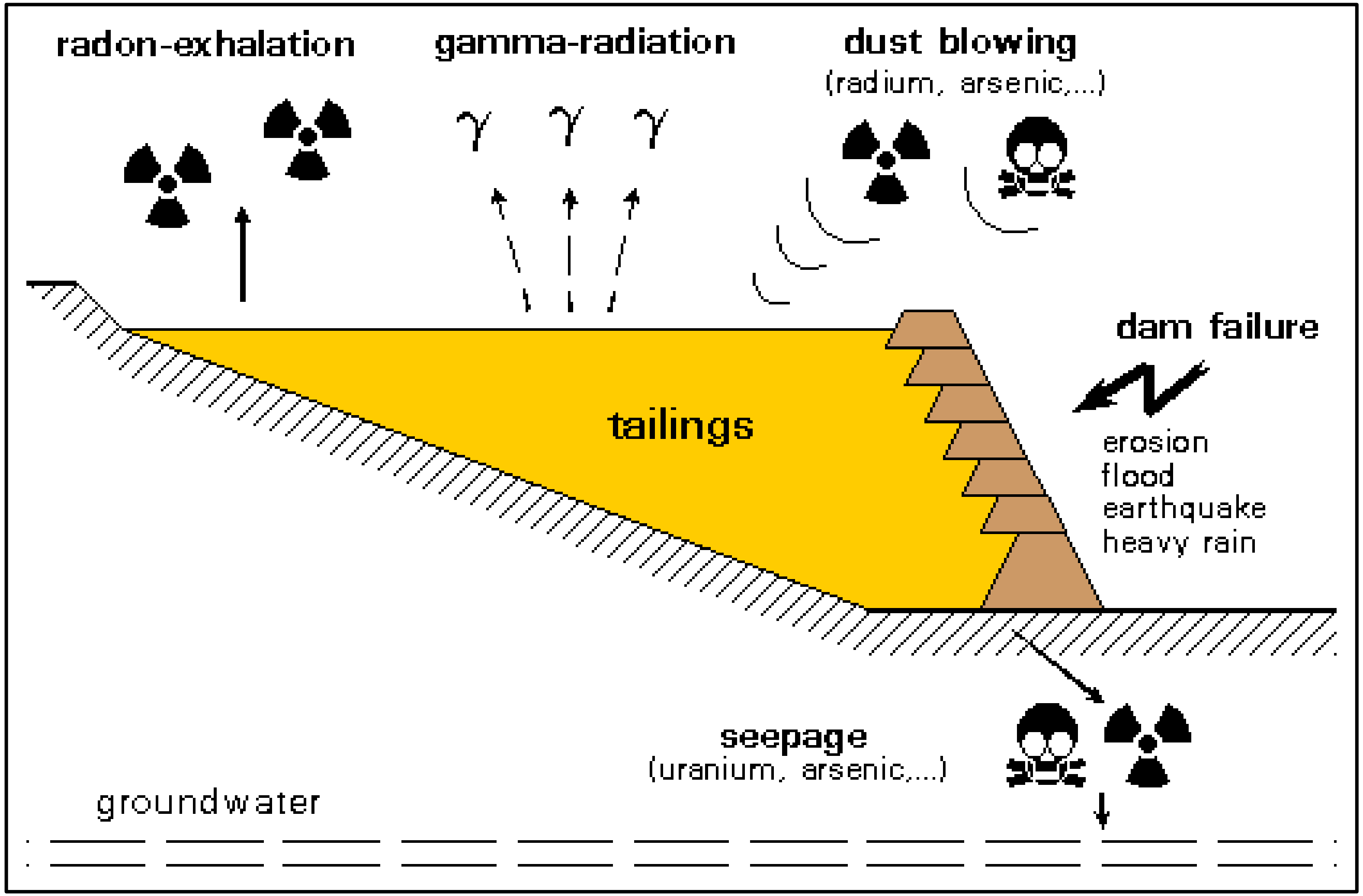


Activity of tailing for ore (grade 0.1% U) after 90% of uranium is extracted

- Secular equilibrium is reached – decay rates for each daughter nuclide are the same.
- Both U-238 and U-234 are removed.

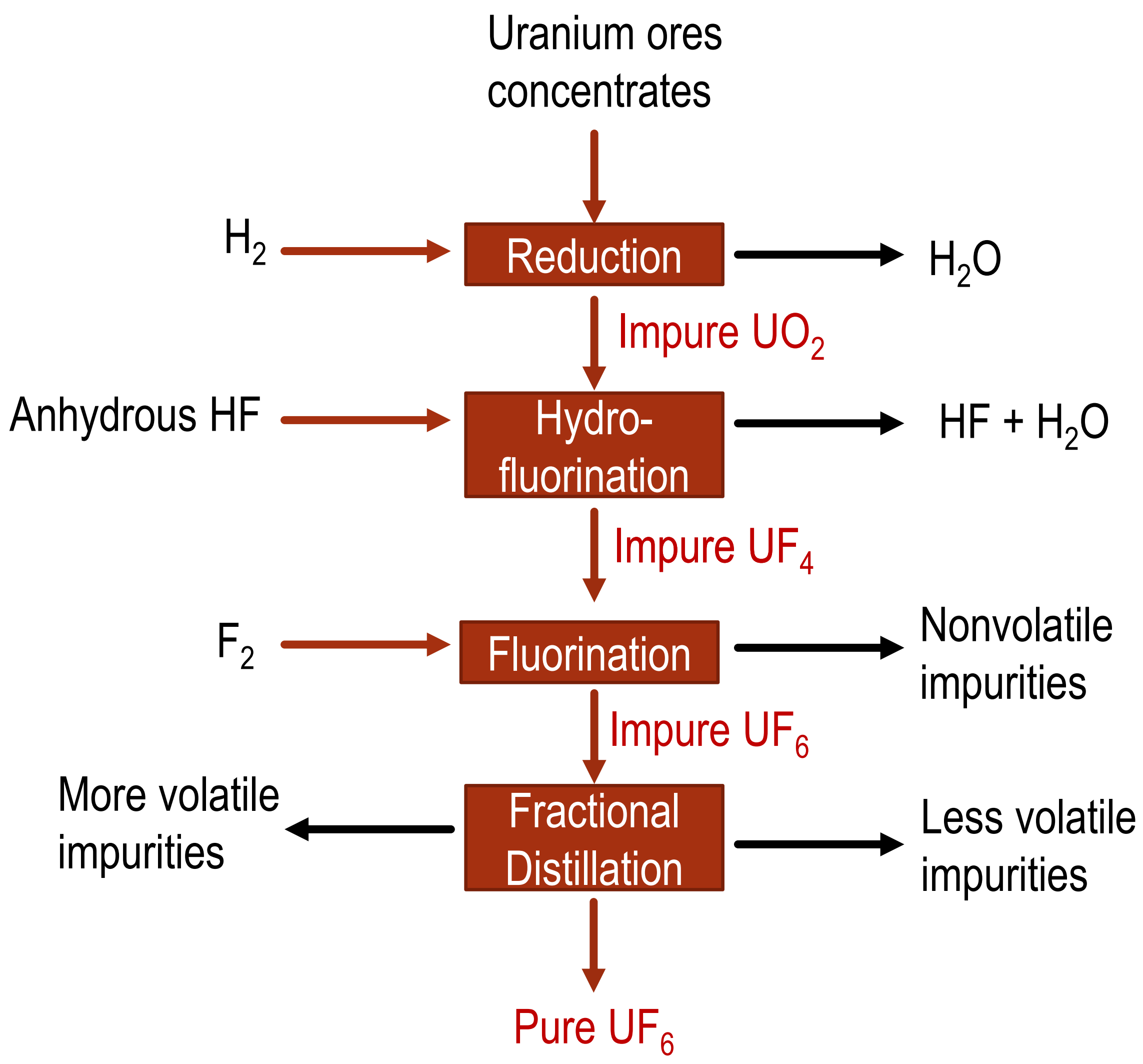
Hazards of Uranium Mill Tailings

- Tailings are slightly radioactive – with decay products of uranium.



Some of the health hazards associated with uranium mill tailings

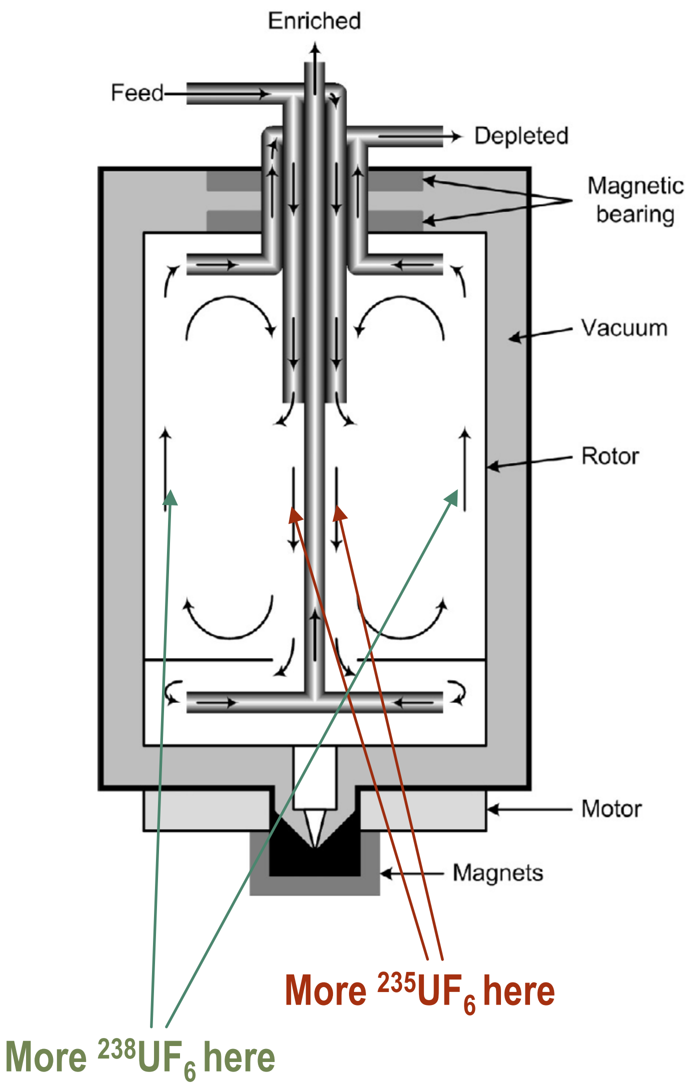
Uranium Conversion (Main Processes)



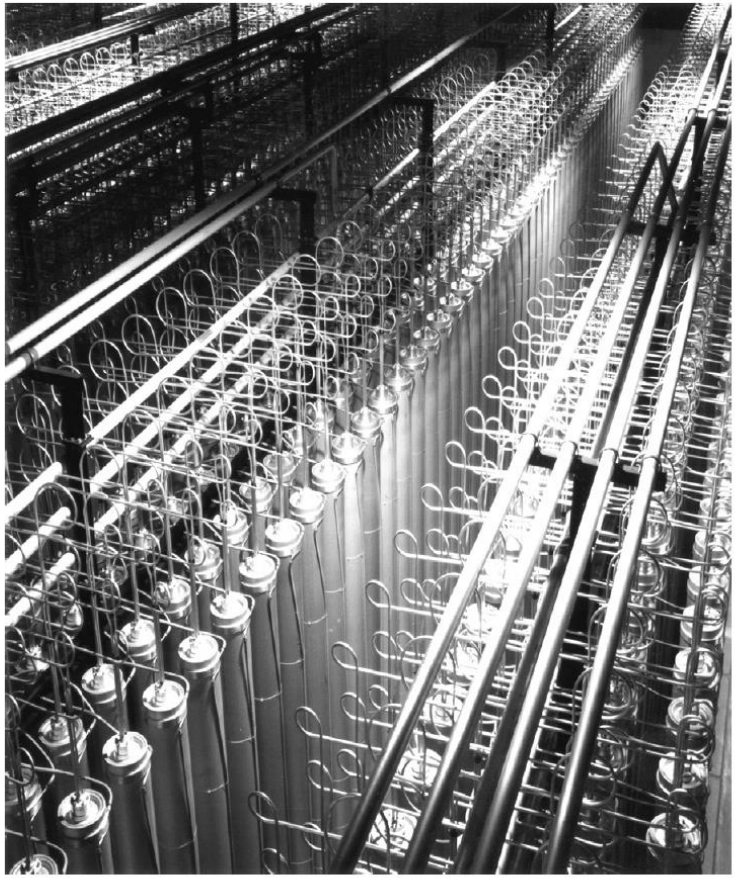
- Process to convert yellow cake to UF_6 (uranium hexafluoride)
- UF_6 – gaseous state – more suitable for the next stage of enrichment)
- Hazards at this point are more chemical in nature (use of HF, F_2) and risk of explosion (H_2)
- Critical condition (chain reaction) is not possible since natural uranium contains only 0.7% of fissile ^{235}U.

Uranium Enrichment (Gas Centrifuge)

- From natural uranium (0.7% ^{235}U, 99.3% ^{238}U) to enriched uranium (3-5% ^{235}U, 95-97% ^{238}U)



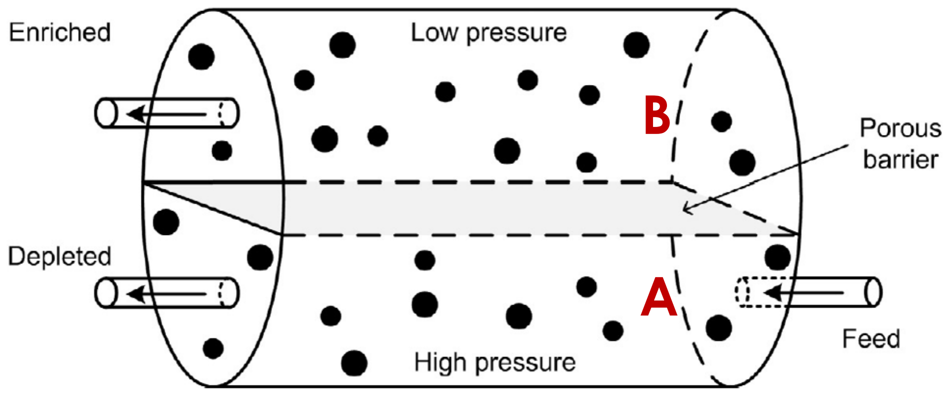
- 1% mass difference ($^{235}UF_6$ & $^{238}UF_6$)
- Centrifugal force – “outwards force” on object moving in a circle.
- In a rotating container, denser media tends to move outwards while lighter media inwards
- $^{235}UF_6$ tends to move inwards while $^{238}UF_6$ outwards
- More $^{235}UF_6$ collected in the inner tube.
- Effect is quite small – needs many stages to reach even 4% enrichment.



Uranium Enrichment (Gaseous Diffusion)

- Depends on the small difference in speed of $^{235}UF_6$ & $^{238}UF_6$ molecules
- A-level Physics (Kinetic Theory of Gases): At same temperature, different species of gas molecules have the same average kinetic energy

$$KE = \frac{1}{2} m_H v_H^2 = \frac{1}{2} m_L v_L^2 \Rightarrow \frac{v_L}{v_H} = \sqrt{\frac{m_H}{m_L}}$$



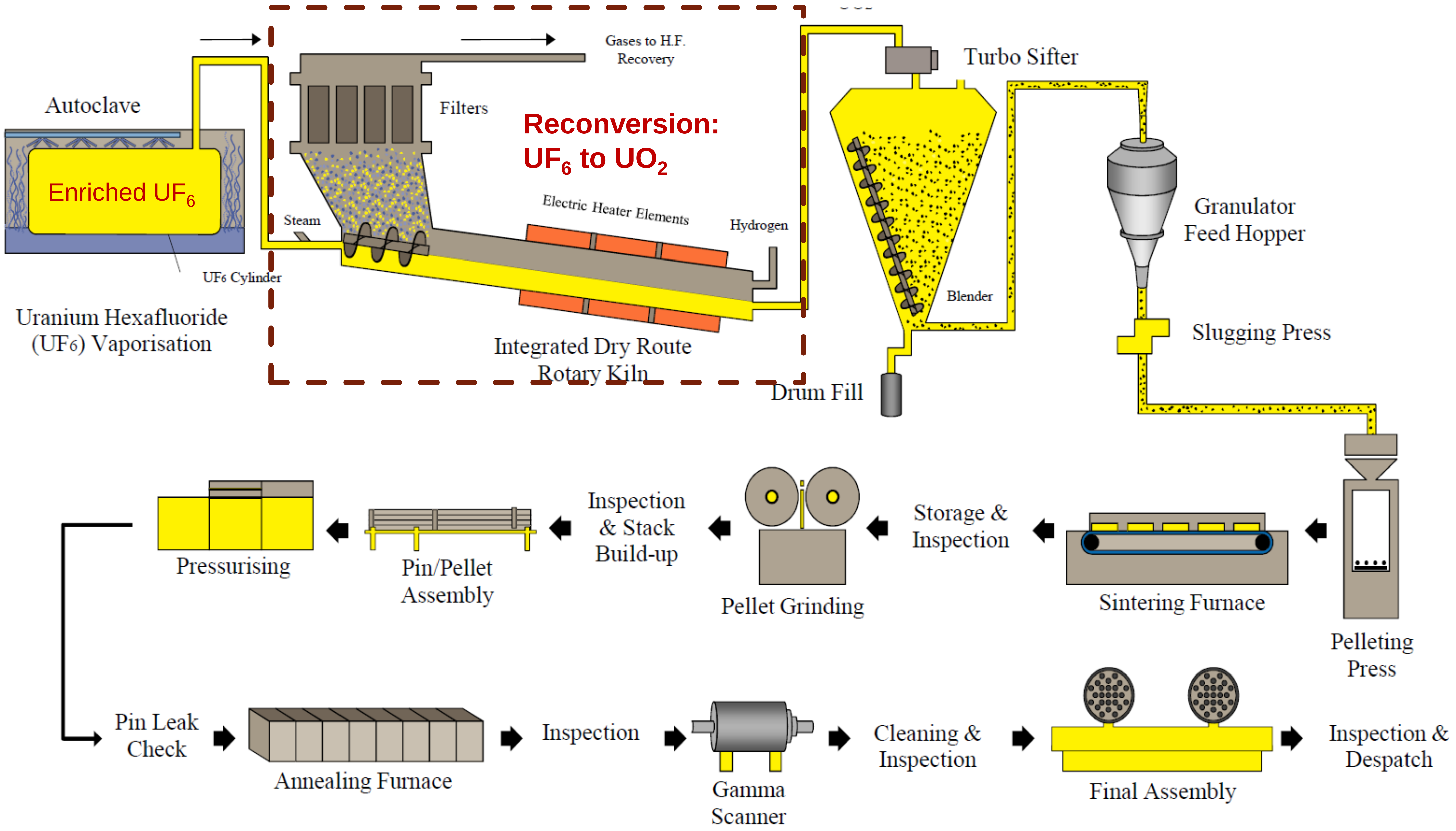
- $^{235}UF_6$ is lighter than $^{238}UF_6$ and has a higher random velocity.
- In Region A, $^{235}UF_6$ impinges the porous barrier more often (more $^{235}UF_6$ goes through the barrier into region B)
- Region B will end up have a larger percentage of $^{235}UF_6$ than in Region A (more enriched)

- Again, the effect is very small (0.4% difference in velocity or diffusion rate) and many stages are needed.

Depleted Uranium

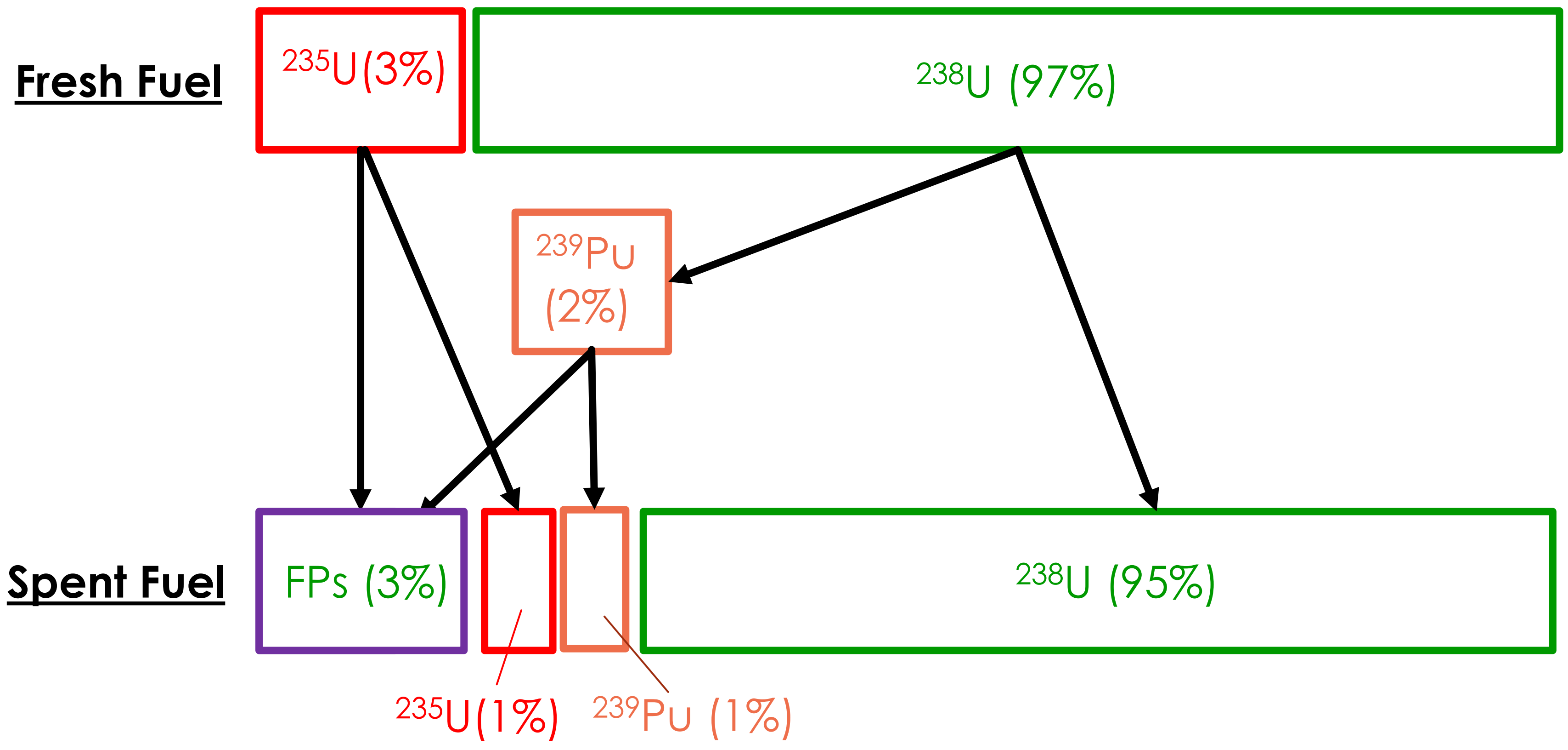
- By-product from uranium enrichment process (as UF_6)
- Contains less than 0.3% ^{235}U. Slightly less reactive than natural uranium.
- High density of 19.1 g/cm^3 – many uses:
  - Counterweights in aircraft
  - Radiation shielding in medical radiation therapy and industrial radiography equipment
  - Containers for transporting radioactive materials
  - Armor plating and armor-piercing projectiles
- Also used in colouring in consumer products
- Estimated world stock of depleted uranium: 1,188,273 tonnes (2008)
- Health concerns:
  - Chemical toxicity – a million times greater *in vivo* than its radiological hazard
  - Radiological toxicity is a concern too.

Fuel Assembly Manufacturing



Fission in Reactor

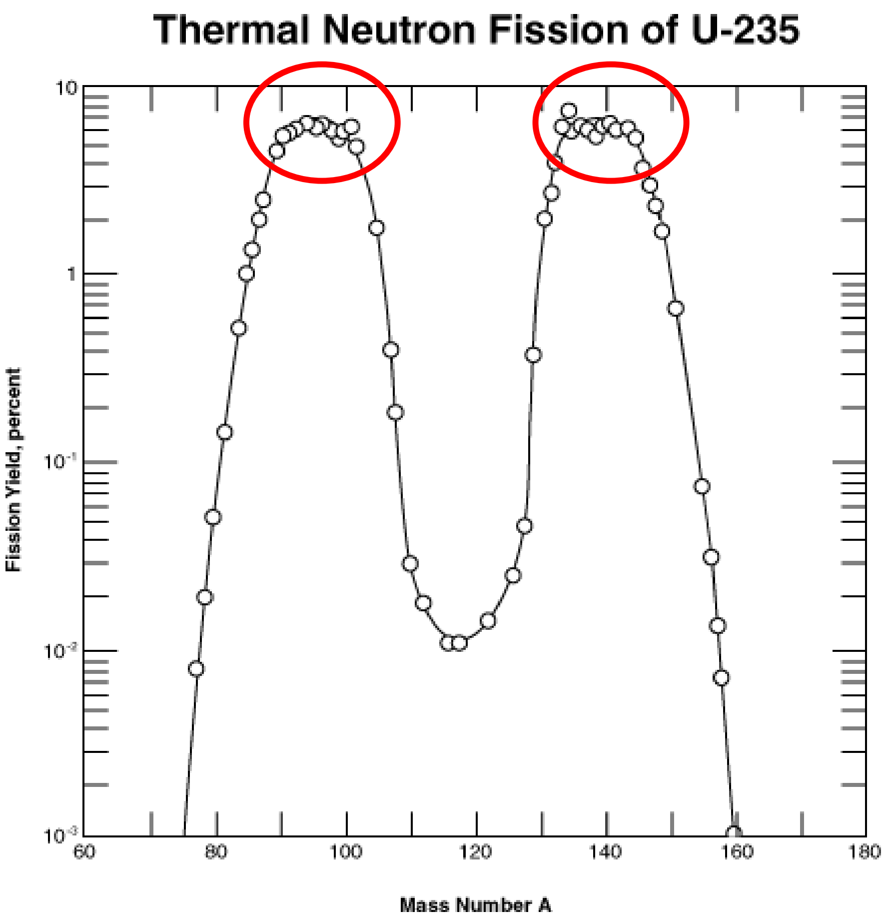
- Fuel assemblies in reactors for about 3 years – depending on reactor design.
- Significant portion of U-235 → Fission Products [giving us energy]
- About 2% of U-238 → Pu-239 (partially) → Fission Products [giving us energy]

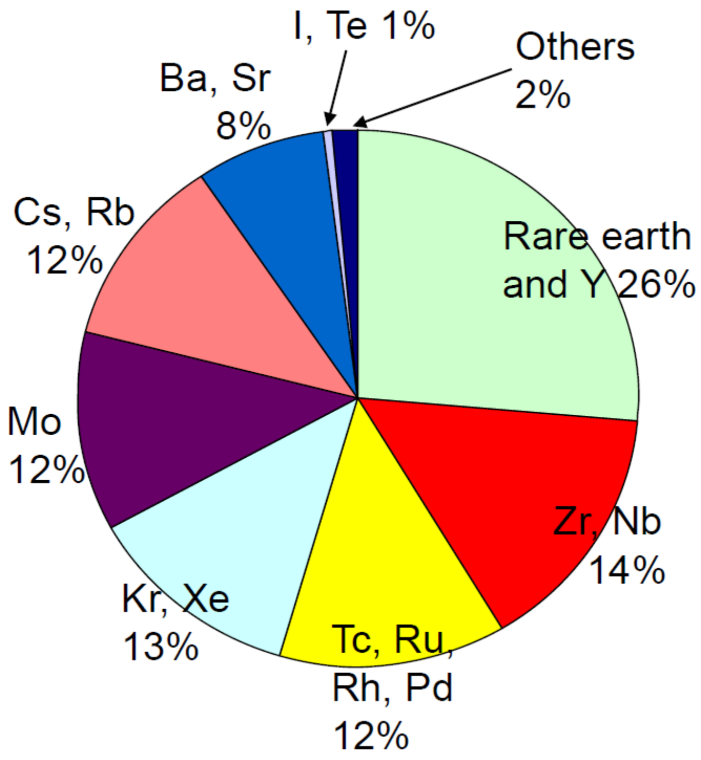


Note: Percentages are approximate and there are other isotopes of Pu too

Fission Products

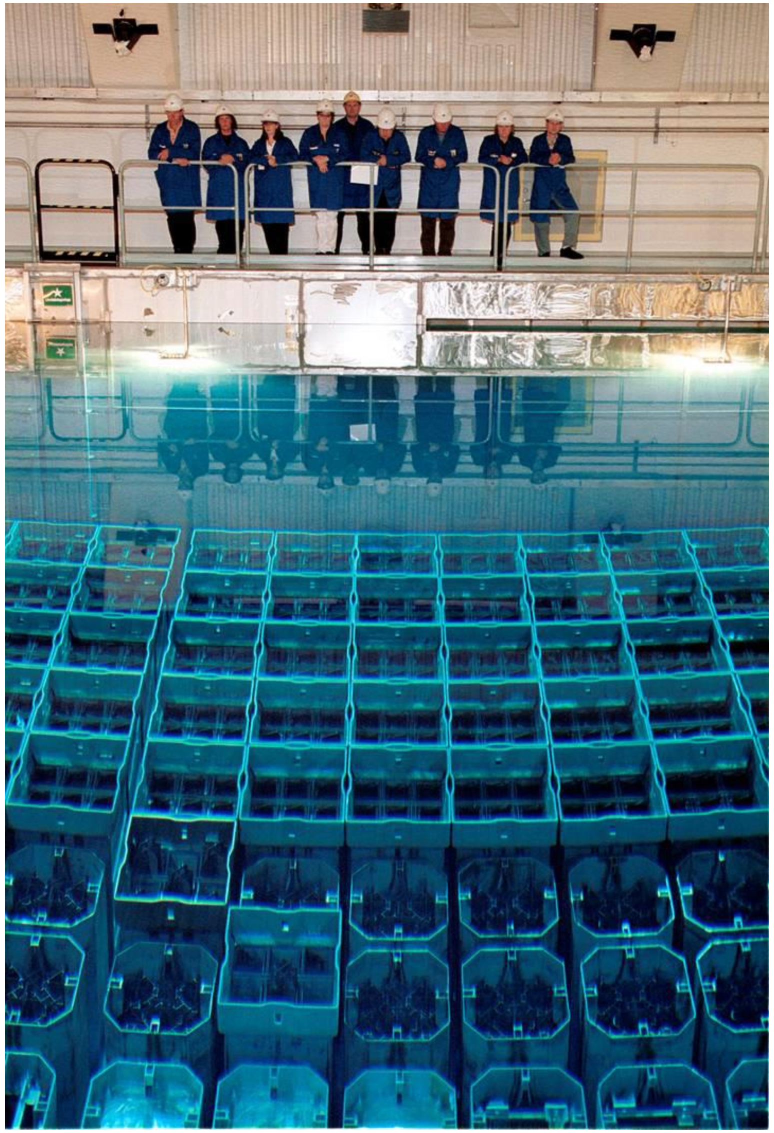
- Spent fuels are many times more radioactive than fresh fuels because of the fission products which have much shorter half-lives.
- Significant decay heat is also present – need to be cooled initially or it will melt.





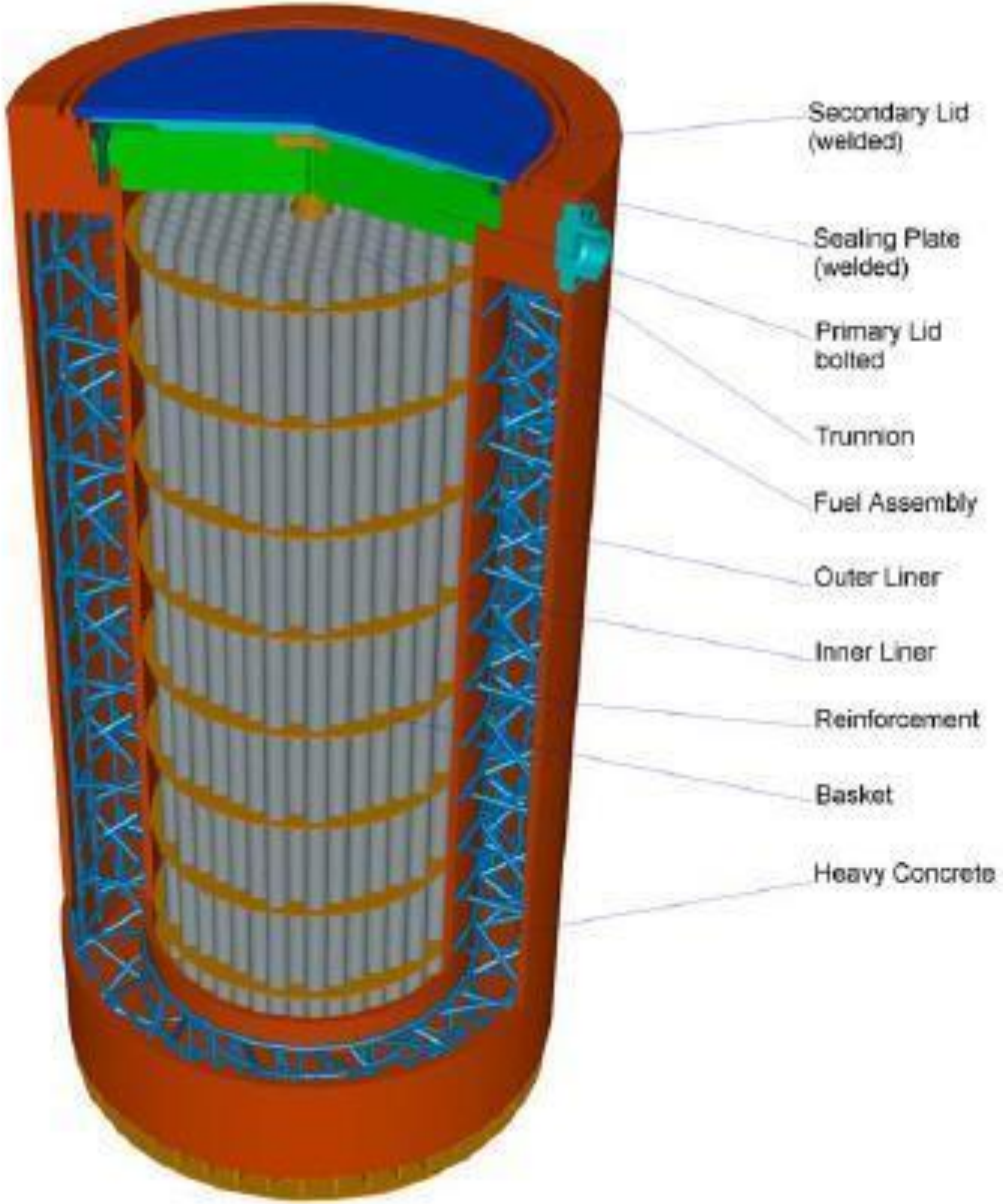
Spent Fuel Pools

- Within the NPP – where used fuels from reactor are stored typically for 5 – 10 years for most of the fission products to decay.
- Typically, 12 m deep with the bottom 5 m equipped with storage racks designed to hold fuel assemblies removed from reactors.
- Water – acts both as a radiation shield as well as for cooling.
- Spent fuel pools lined with stainless steel – prevent leaks
- High-density racks incorporate boron-10, often as boron carbide or other neutron-absorbing material to ensure subcriticality.
- Water quality is tightly controlled to prevent the fuel or its cladding from degrading
- If there is a prolonged interruption of cooling due to emergency situations, the water in the spent fuel pools may boil off, possibly resulting in radioactive elements being released into the atmosphere. *This was a possible scenario in the Fukushima accident which fortunately did not happen.*



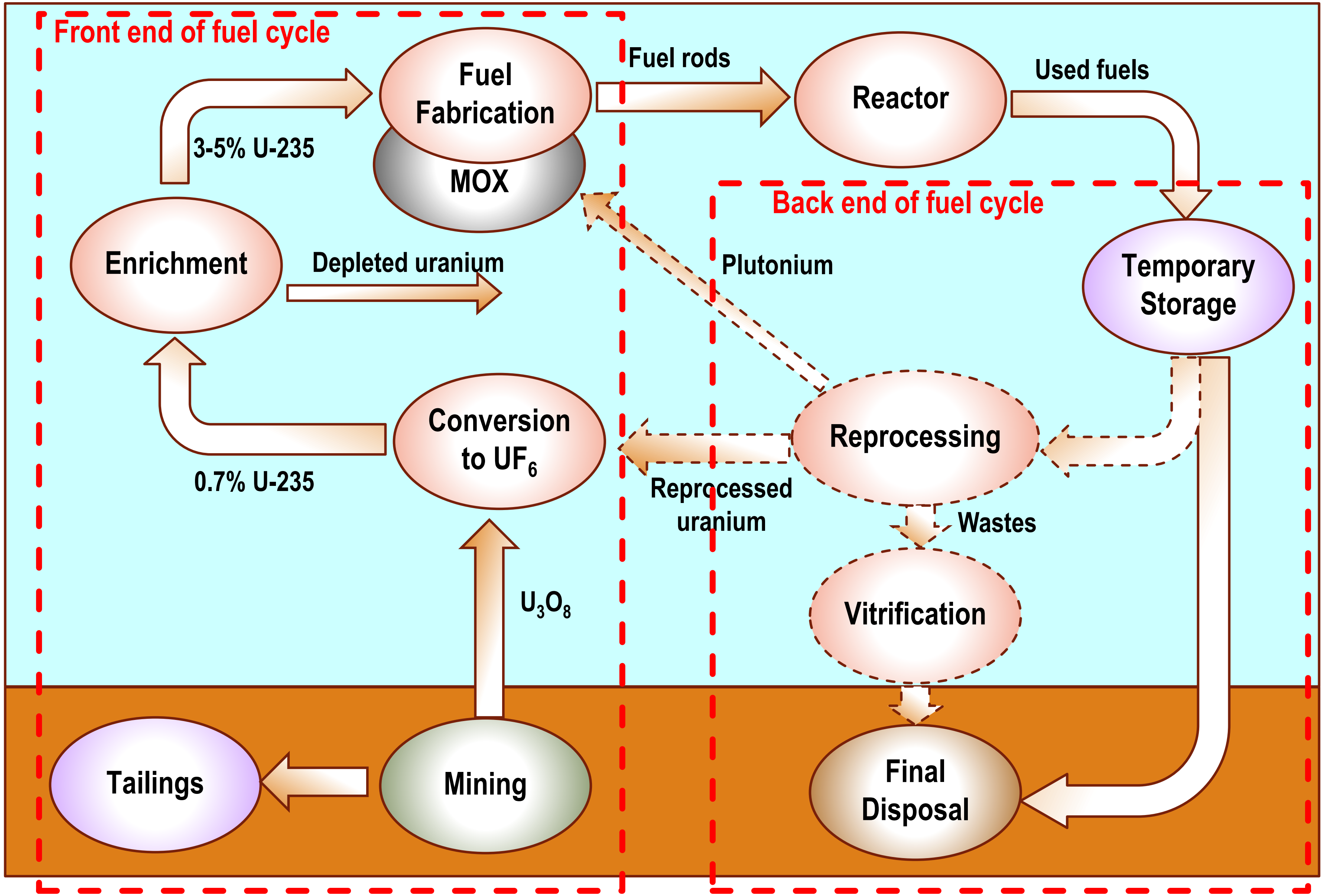
Dry Casks

- When used fuels are sufficiently cooled, transfer to dry cask.
- Filled with inert gas and welded. Concrete to act as radiation shield and steel outer liner to withstand harsh weather conditions.
- Cooled externally by natural air circulation
- Usually located at reactor site. Radiation level around casks monitored.



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

Nuclear Fuel Cycle



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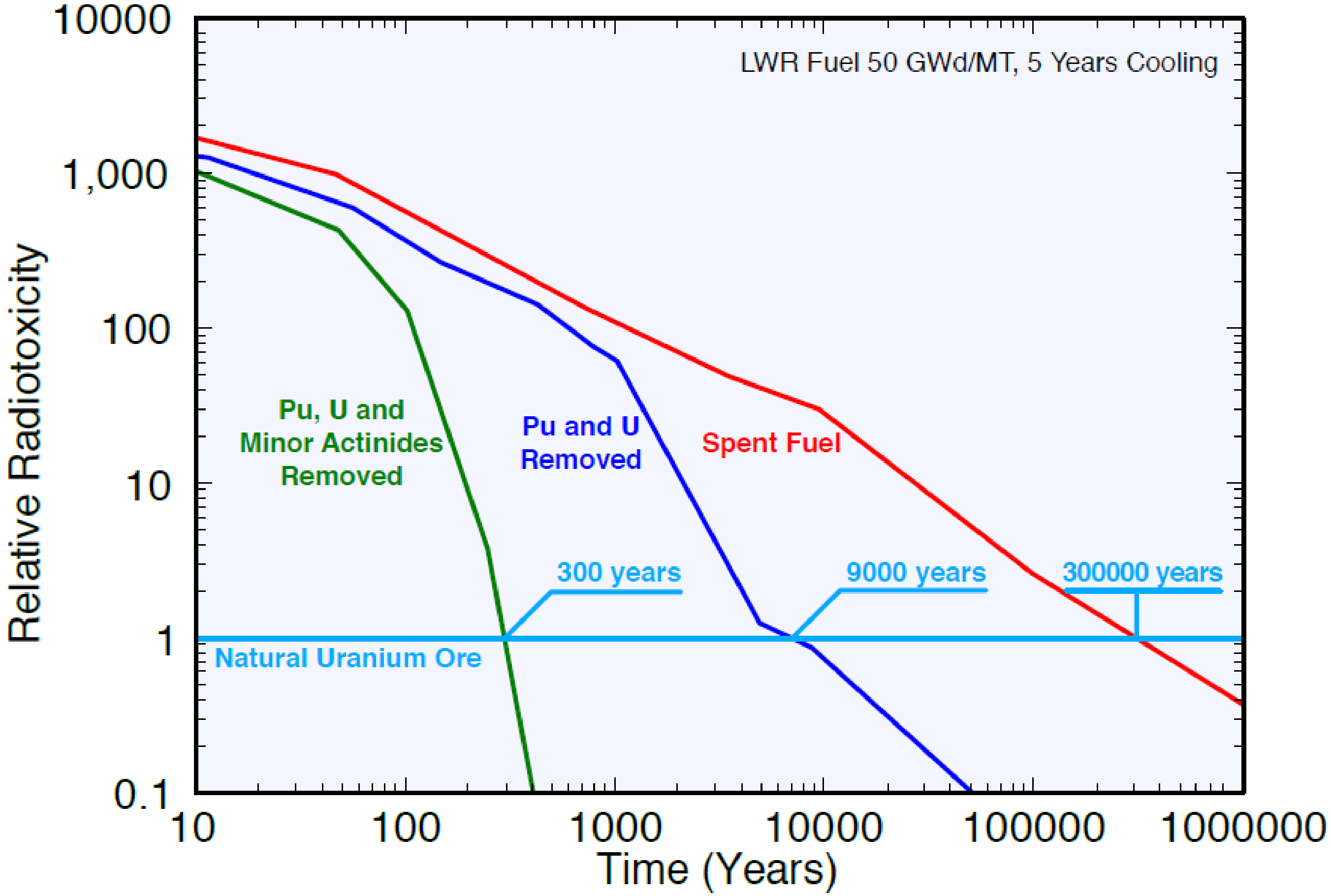
Reprocessing

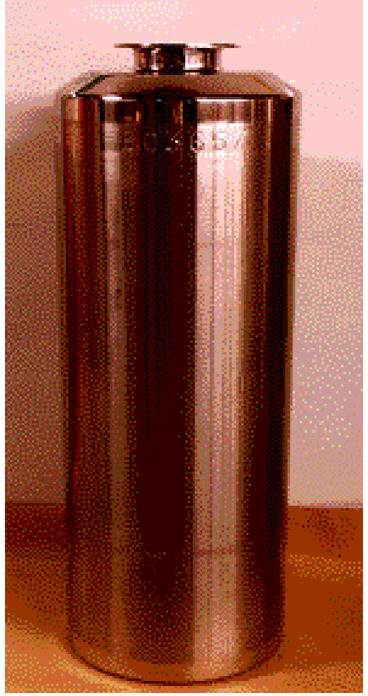
- Chemically separating plutonium and / or uranium from spent fuel – may also be possible to remove other minor actinides (americium, neptunium, curium, etc.)
- Completing the cycle allows more efficient use of uranium (more of ^{238}U is used).
- Reduce the time needed for radioactivity to drop to level of natural uranium ore.



- Reprocessing is controversial due to the increased risk of nuclear proliferation and nuclear terrorism.
- Economical viability is another factor.

Vitrification

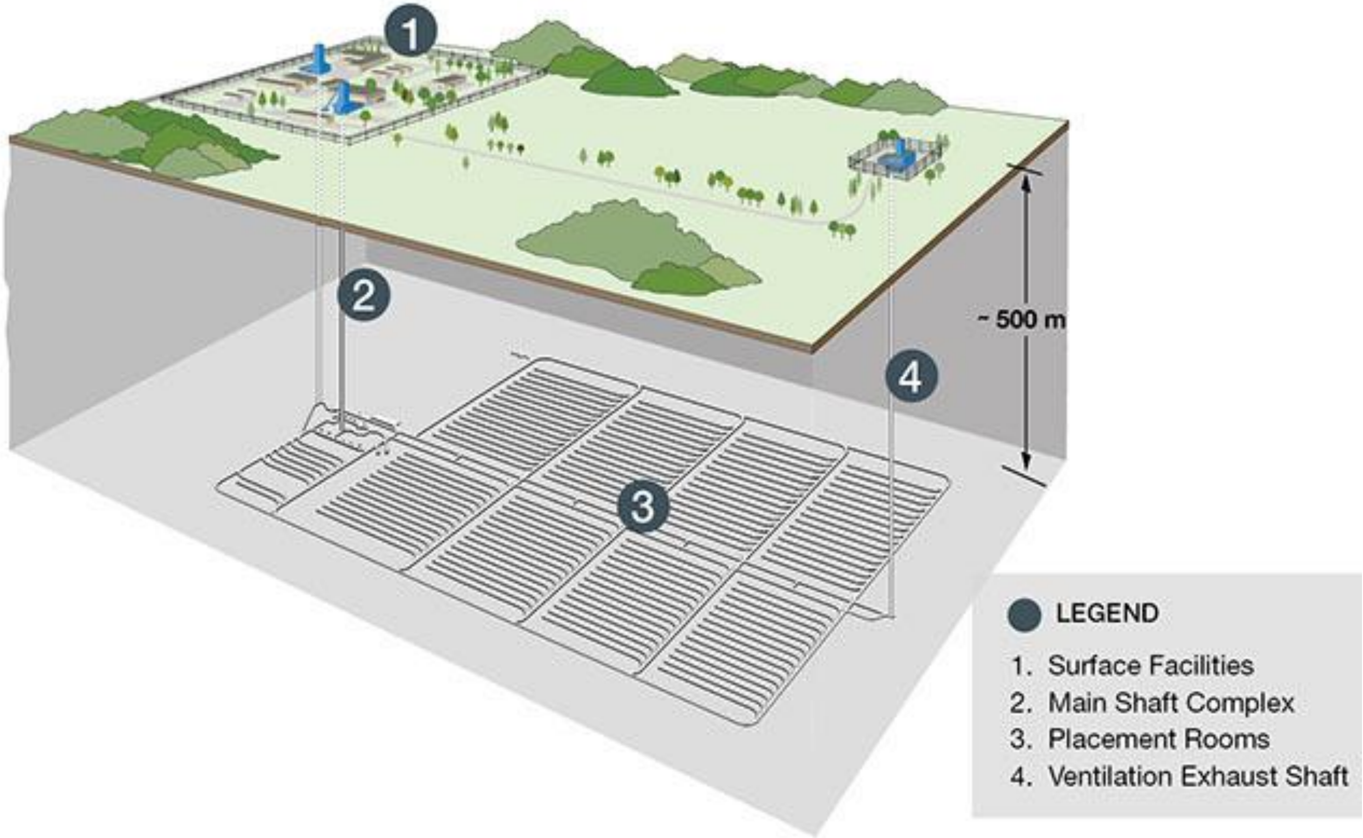
- Reprocessing results in high level waste (HLW) comprising fission products and some transuranic elements) in liquid form.
- Need to immobilize this HLW into an insoluble, solid waste form that will remain stable for many thousands of years.
- Vitrification process:
  - Waste is dried to a granular powder.
  - Incorporated into molten borosilicate glass,
  - Poured into a robust stainless steel canister about 1.3 metres high, and allowed to cool, forming a solid matrix.
  - Container welded closed and are ready for storage and final disposal



- Used in France, Japan, Russia, UK, and USA
- Experts are also considering in situ vitrification – a means of 'fixing' radioactivity in contaminated ground as well as creating a barrier to prevent further spread of contamination

Deep Geological Repository

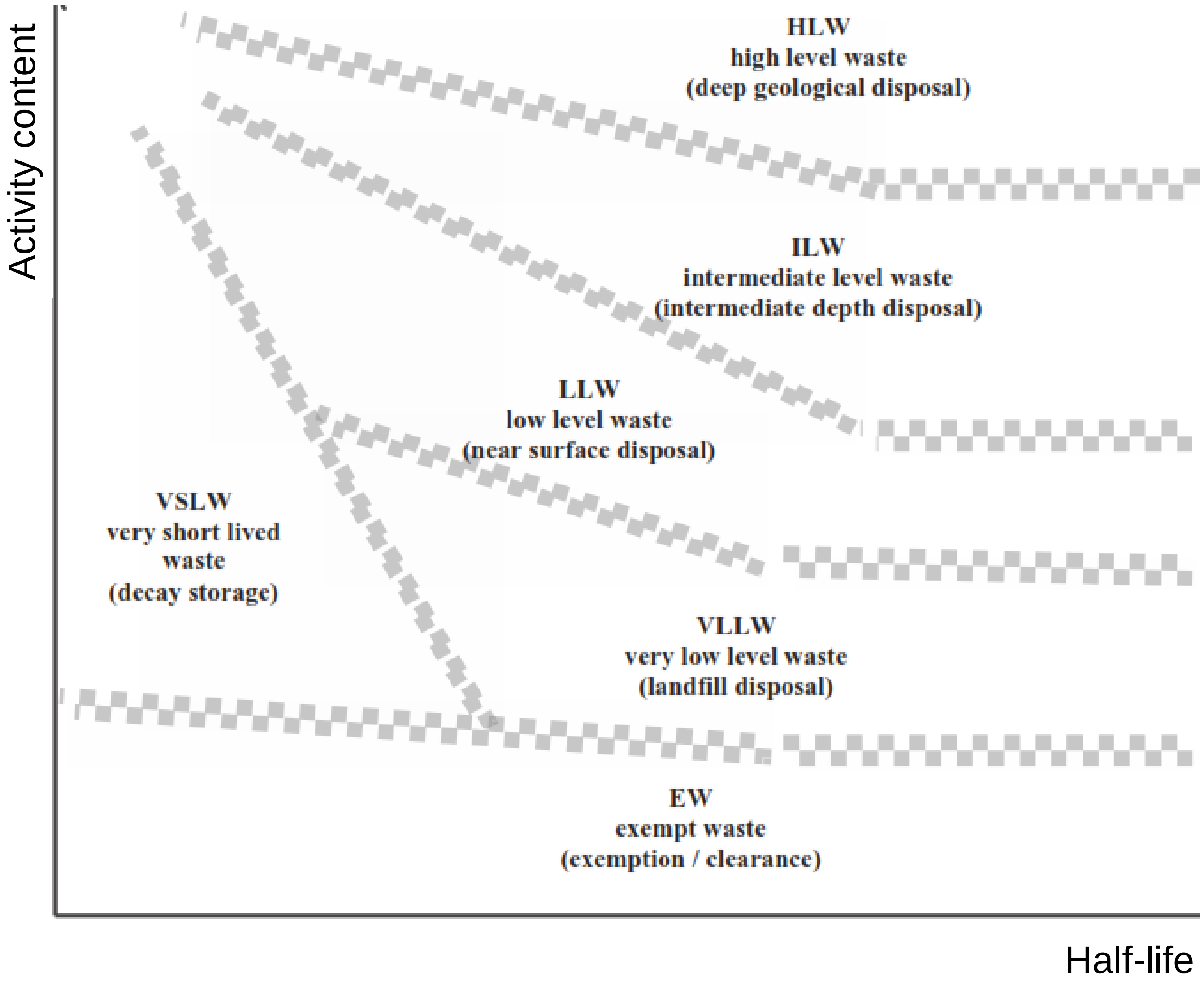
- A network of underground tunnels and placement rooms for used nuclear fuel containers – to isolate used fuel over long term.
- Typical depth of 250 – 1000 m
- Multiple-barrier concept – fuel pellet, zirconium cladding, used nuclear fuel container, encased bentonite clay buffer box, geosphere (rock).
- Monitoring programme for ground and surface water, radiation, air quality, fire, etc.
- Some may require the possibility of retrieving the used fuel in future.



- Another concept in serious consideration is deep borehole of up to 5,000 m with the upper portion sealed off

https://www.nwmo.ca/en/A-Safe-Approach/Facilities/Deep-Geological-Repository

Classification of Radioactive Waste & Disposal



https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1419_web.pdf

Class	Description	Disposal
HLW	Very high activity (10^4 – 10^6 TBq/m^3), heat from FPs (2 – 20 kW/m^3), e.g., spent fuel, wastes from reprocessing,	Several 100s m underground / deep boreholes
ILW	Long-lived isotopes, especially α-emitter, no/limited provision for heat dissipation	10s to a few 100s m underground
LLW	Above exemption limit, limited amount of long-lived isotopes	Engineered near surface facilities
VLLW	May not meet EW criteria but does not need containment, e.g., soil and rubble.	Landfill facility
VSLW	Half-life < 100 days, e.g., isotopes for medical purposes	Stored for decay (~ a few years)
EW	Meets the criteria for clearance or exemption, eff dose < 10 μSv/yr.	Treated as conventional wastes

Opposing Views on Nuclear Waste Disposal

- Large range of opinions on the intrinsic serious of nuclear waste disposal.
- On impact for future generation, e.g., Allen Kneese of Resources for the Future: "Here we are speaking of hazards that may **affect humanity many generations** hence and equity questions that can **neither be neglected as inconsequential** or **evaluated on any known theoretical or empirical basis**. This means that **technical people, be they physicists or economists, cannot legitimately make the decision to generate such hazards**. Our society confronts a problem of great moral profundity; in my opinion it is one of the most consequential that has ever faced mankind. In a democratic society the only legitimate means for making such a choice is through the mechanisms of **representative government**.
- Most experts do not contest the question of moral responsibility but frustrated by the emphasis on this issue because they believe that the concern is highly exaggerated.
- Sir John Hill, former Chairman of UK Atomic Energy Authority: "I've never come across any industry where **the public perception of the problem is so totally different from the problems as seen by those of us in the industry**."

General Considerations in Nuclear Waste Disposal

- Universally agreed that nuclear wastes must be disposed of in a “safe” manner. However, criteria for safety raises diverse questions, such as:
  - Nature and kind of standard – based on dose or calculated cancer risk? On individuals or collectively, local or global populations?
  - Time period of concern – how far into the future, 100, 1,000, or even 1,000,000 years?
  - Our picture of our descendants – technologically more advanced, able to protect themselves better or at least not worse?
  - Context for considering nuclear waste hazards – in isolation or in relation to other hazards?
  - Decision making process – based on technical experts, views of public, different levels of government?
  - Intergenerational and intragenerational equity – compare benefits and risks to current and future generations, or even between different countries in current generation.
- May not have easy answers or accepted methodologies to converge to common conclusions.
  - Examples: Yucca Mountain Nuclear Waste Repository, disposal of water accumulated in Fukushima NPP.