Nuclear Fuel Cycle

Mining-Fuel Rods-Recycling-Waste Management

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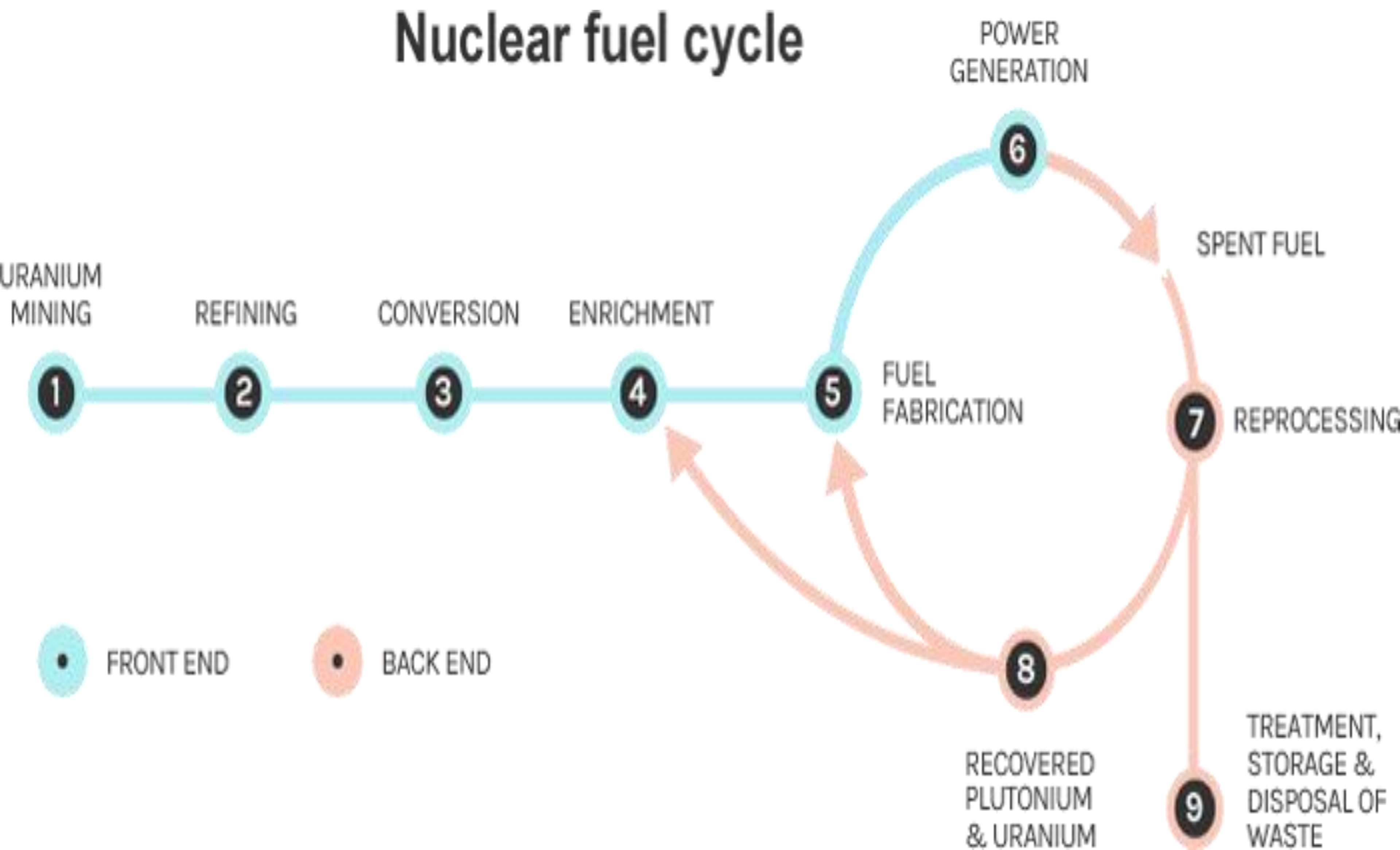
Fissile Nuclear Fuels

- Nuclear materials which can undergo fission under thermal conditions is called a nuclear fuel.
- The most common fissile nuclear fuels are uranium-235 (^{235}U) and plutonium-239 (^{239}Pu).
- Nuclear fuel has the highest energy density of all practical fuel sources.

Fuel Cycle



Nuclear fuel cycle
POWER GENERATION
6
SPENT FUEL
URANIUM MINING
REFINING
CONVERSION
ENRICHMENT
1
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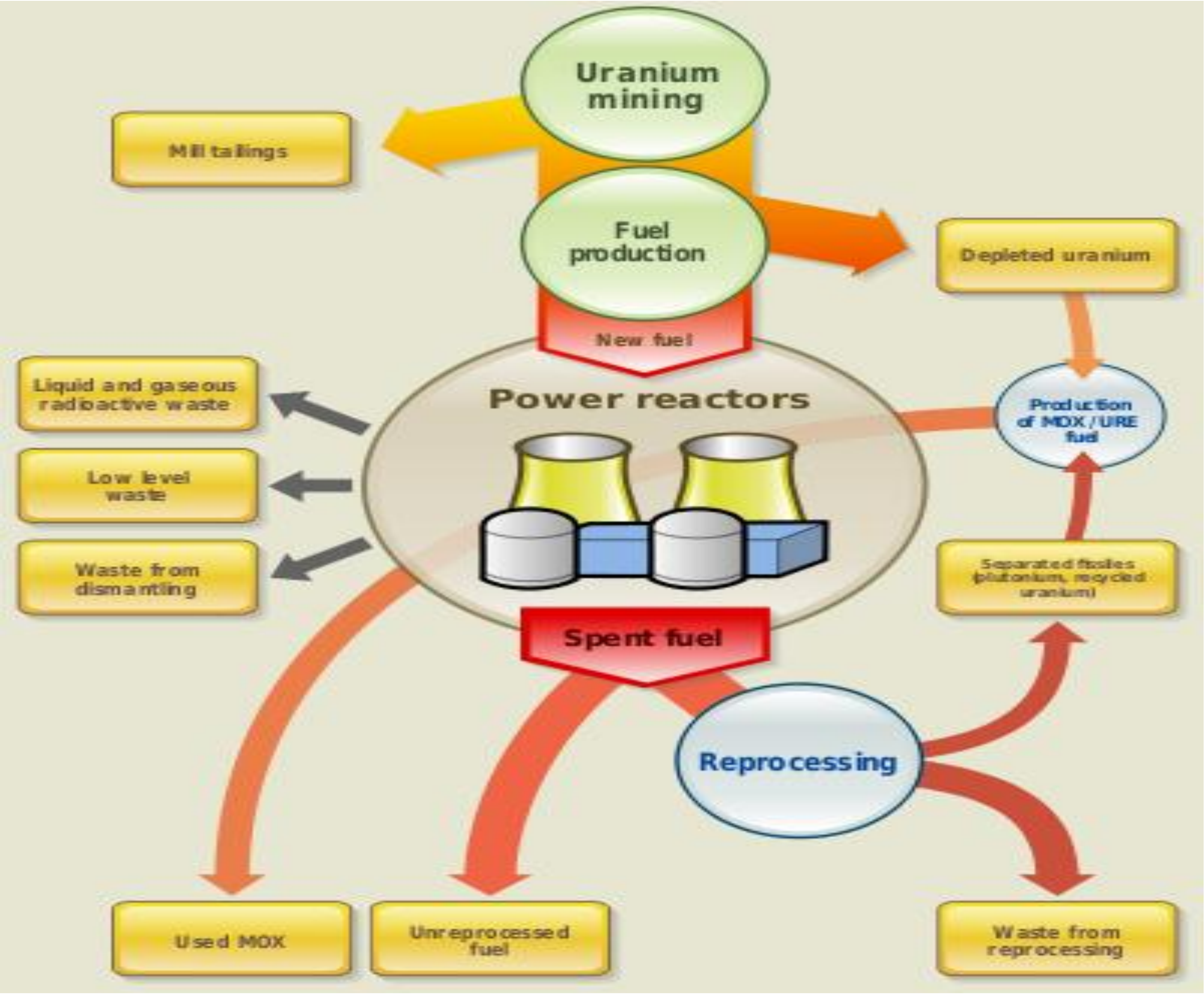
4
5
FUEL FABRICATION
7
REPROCESSING
FRONT END
BACK END
8
RECOVERED PLUTONIUM & URANIUM
9
TREATMENT, STORAGE & DISPOSAL OF WASTE

Nuclear Fuel Cycle



Uranium Mining

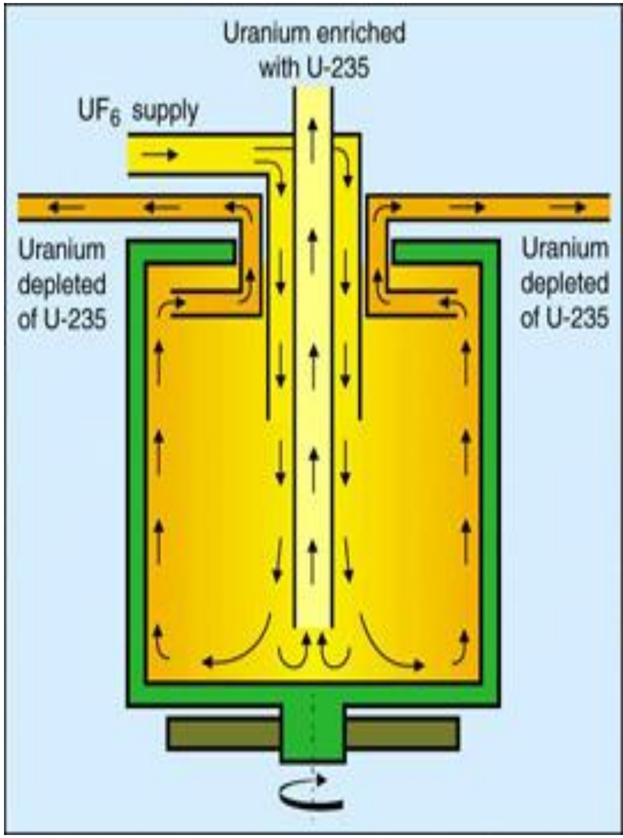
- Uranium mines operate in some twenty countries, though about half of world production comes from just ten mines in six countries, in Canada, Australia, Niger, Kazakhstan, Russia and Namibia.
- At conventional mines, the ore goes through a mill where it is first crushed. It is then ground in water to produce a slurry of fine ore particles suspended in the water. The slurry is leached with sulphuric acid to dissolve the uranium oxides, leaving the remaining rock and other minerals undissolved.
- Both mining methods produce a liquid with uranium dissolved in it. This is filtered and the uranium then separated by ion exchange, precipitated from the solution, filtered and dried to produce a uranium oxide concentrate (U_3O_8), which is then sealed in drums. This concentrate is a bright yellow colour, and is known as 'yellowcake'.
- The U_3O_8 is only mildly radioactive. (The radiation level one metre from a drum of freshly-processed U_3O_8 is about half that - experienced from cosmic rays - on a commercial jet flight.)

Nuclear Enrichment

- The vast majority of all nuclear power reactors require 'enriched' uranium fuel in which the proportion of the uranium-235 isotope has been raised from the natural level of 0.7% to about 3.5% to 5%. The enrichment process needs to have the uranium in gaseous form, so on the way from the mine it goes through a conversion plant which turns the uranium oxide into uranium hexafluoride (UF_6)

Nuclear Enrichment Steps

- The enrichment plant removes about 85% of the uranium by separating gaseous uranium hexafluoride into two streams: One stream is enriched to the required level and then passes to the next stage of the fuel cycle. The other stream is depleted in U-235 and is called 'tails'. It is mostly uranium-238 and has little immediate use.
- Today's enrichment plants use the centrifuge process, with thousands of rapidly-spinning vertical tubes. Research is being conducted into laser enrichment, which appears to be a promising new technology.

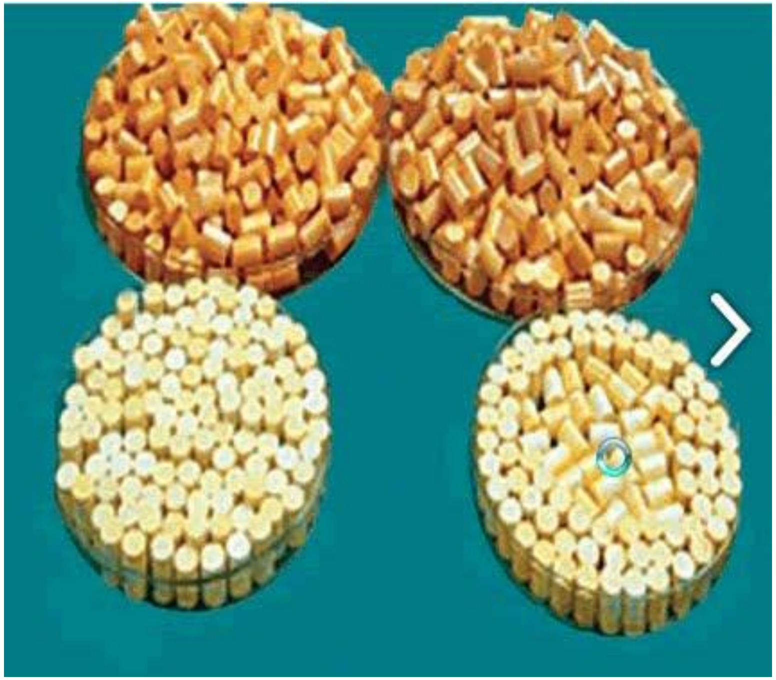


Fuel Fabrication

- Enriched UF_6 is transported to a fuel fabrication plant where it is converted to uranium dioxide (UO_2) powder. This powder is then pressed to form small fuel pellets, which are then heated to make a hard ceramic material. The pellets are then inserted into thin tubes to form fuel rods.

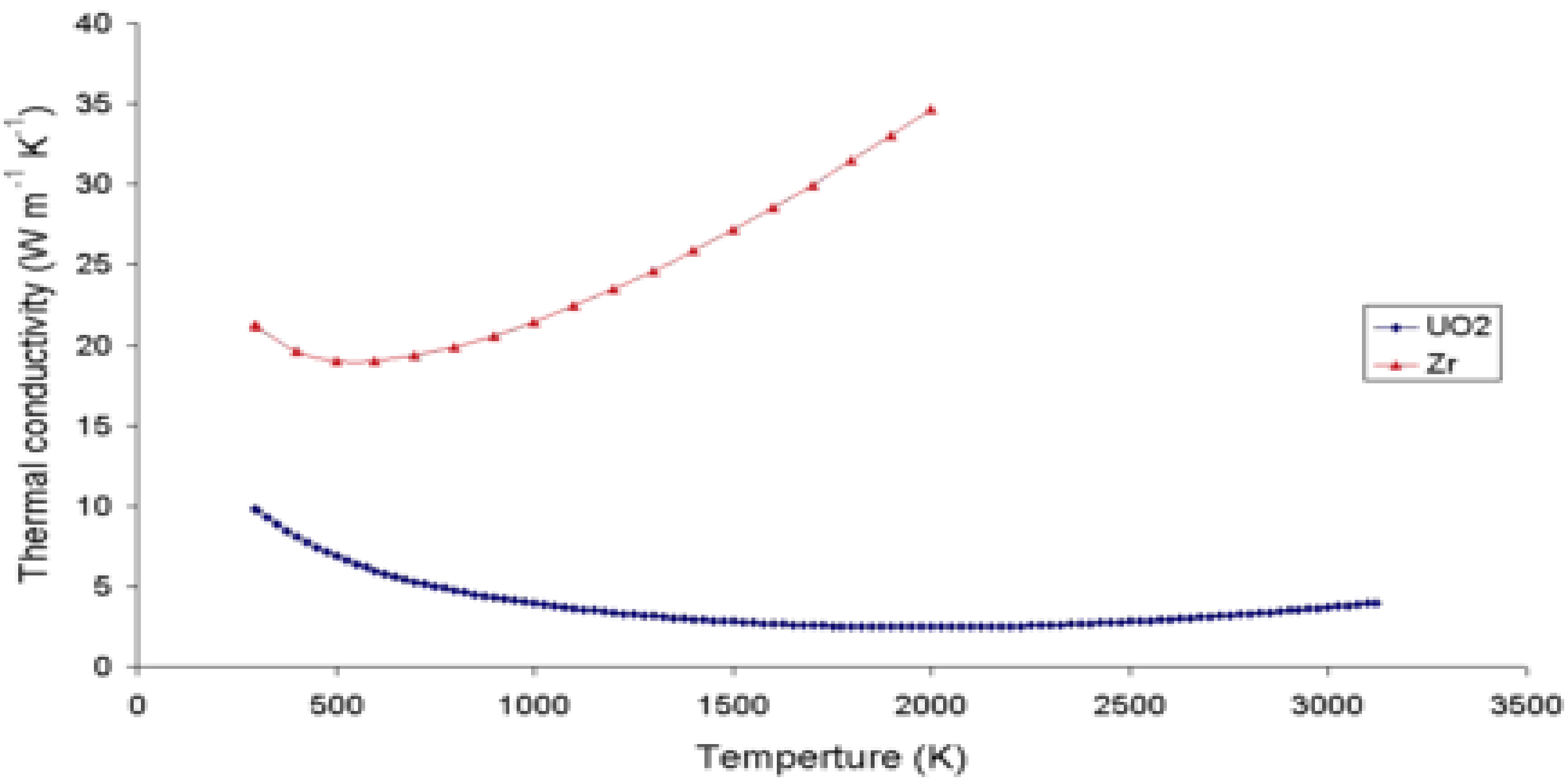
Oxide Fuel

- For fission reactors, the fuel (typically based on uranium) is usually based on the metal oxide; the oxides are used rather than the metals themselves because the oxide melting point is much higher than that of the metal and because it cannot burn, being already in the oxidized state.
- UO_2 (UOX)is then mixed with an organic binder and pressed into pellets, these pellets are then fired at a much higher temperature (in H_2/Ar) to sinter the solid. The aim is to form a dense solid which has few pores.
- **Mixed oxide**, or **MOX fuel**, is a blend of plutonium and natural or depleted uranium which behaves similarly



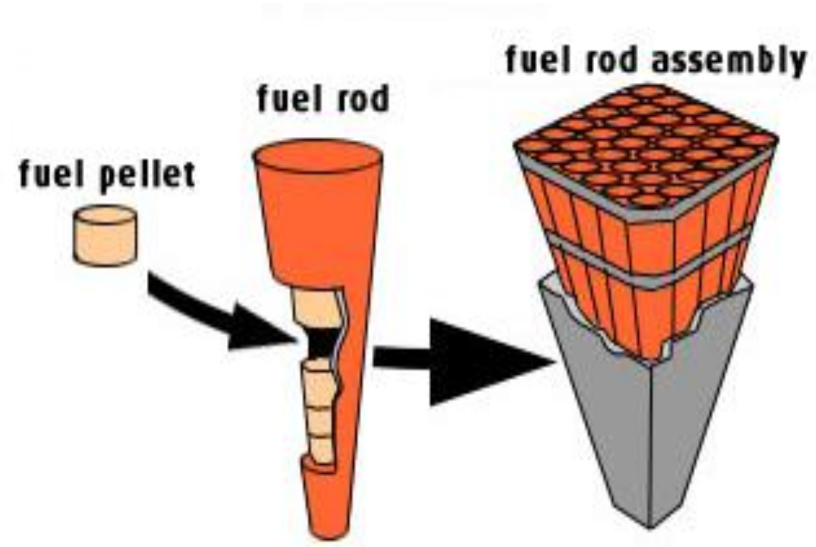
Zirconium and Nuclear Fuels

- Most nuclear fuel for LWR are encased in zirconium rods to protect them from corrosion. Moreover the heat transfer coefficient of zirconium is higher.



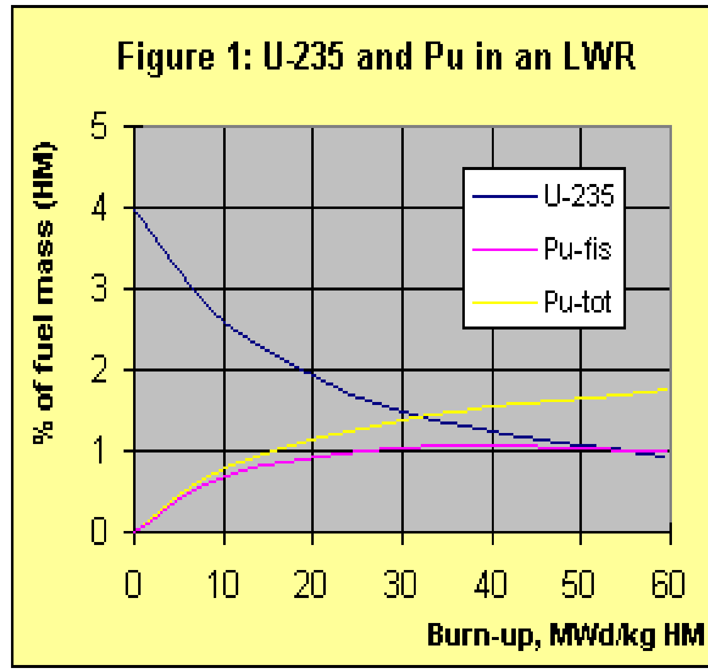
Fuel Rods

- Fuel rods are then grouped together to form fuel assemblies, which are several meters long.
- The number of fuel rods used to make each fuel assembly depends on the type of reactor. A PWR (pressurized water reactor) may use between 121-193 fuel assemblies, each consisting of between 179-264 fuel rods. A BWR (boiling water reactor) has between 91-96 fuel rods per assembly, with between 350-800 fuel assemblies per reactor.



Nuclear Fuel Burnup

- 27 tons of fresh fuel is needed per year for 1000 MW reactor
- Several hundred fuel assemblies make up the core of a reactor. For a reactor with an output of 1000 megawatts (MWe), the core would contain about 75 tonnes of low-enriched uranium.
- Typically, some 44 million kilowatt-hours of electricity are produced from one tonne of natural uranium



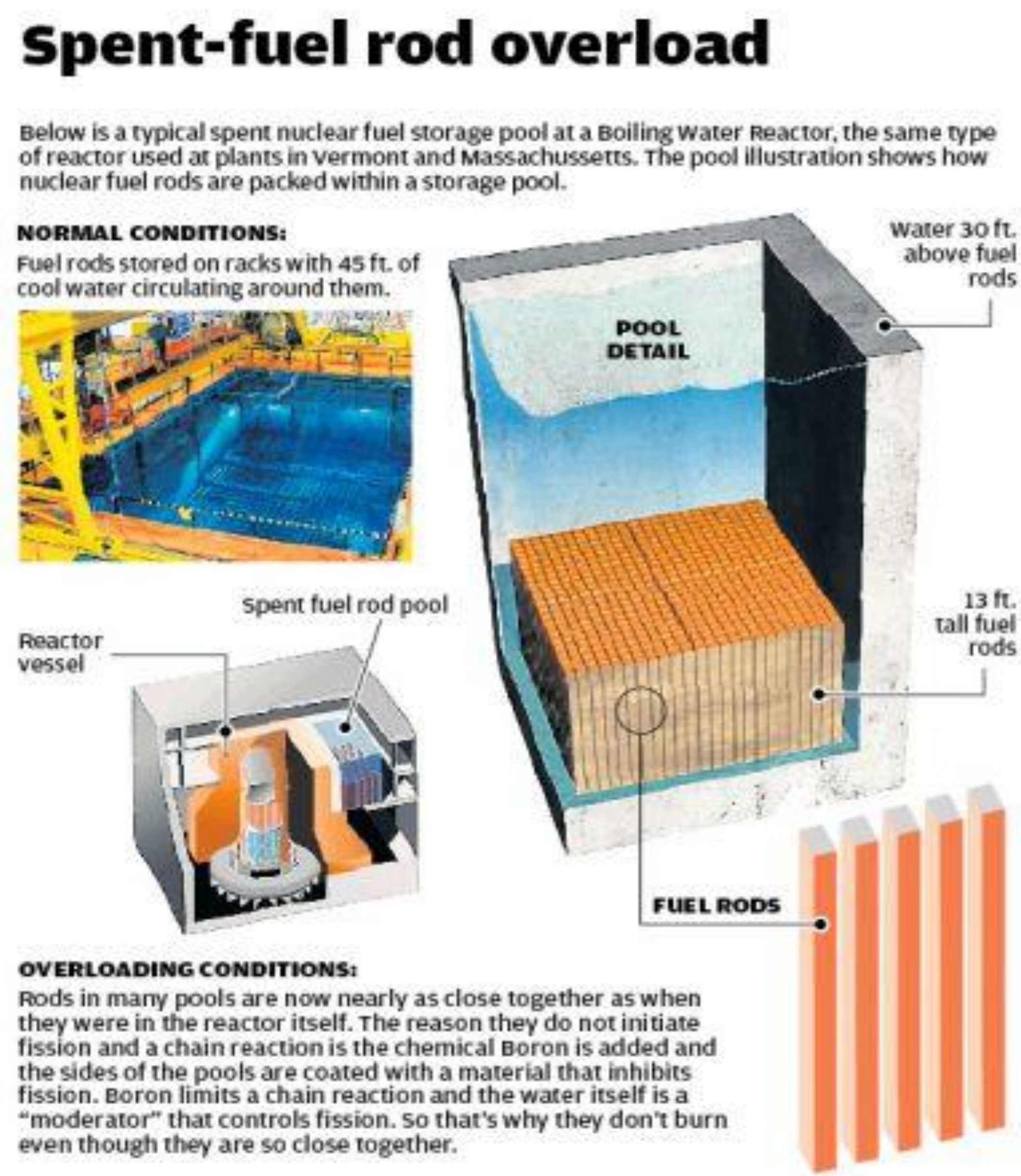
Used Fuel

- With time, the concentration of fission fragments and heavy elements formed in the same way as plutonium in the fuel will increase to the point where it is no longer practical to continue to use the fuel.
- So after 18-36 months the used fuel is removed from the reactor.

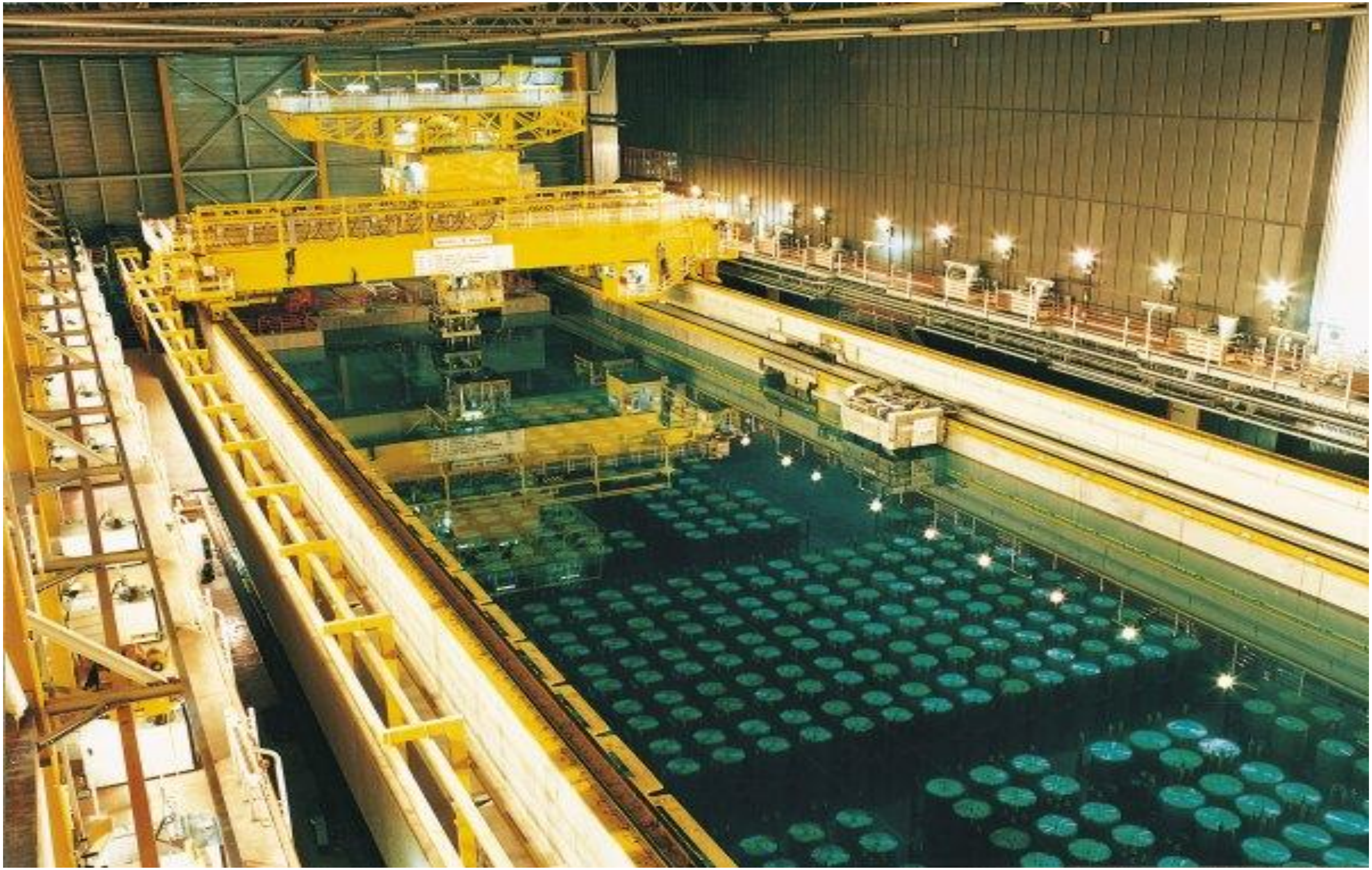
Used Fuel Resting

- When removed from a reactor, the fuel will be emitting both radiation, principally from the fission fragments, and heat. It is unloaded into a storage pond immediately adjacent to the reactor to allow the radiation levels to decrease. In the ponds the water shields the radiation and absorbs the heat, which is removed by circulating the water to external heat exchangers.
- Used fuel is held in such pools for several months and sometimes many years. It may be transferred to naturally-ventilated dry storage on site after about five years.

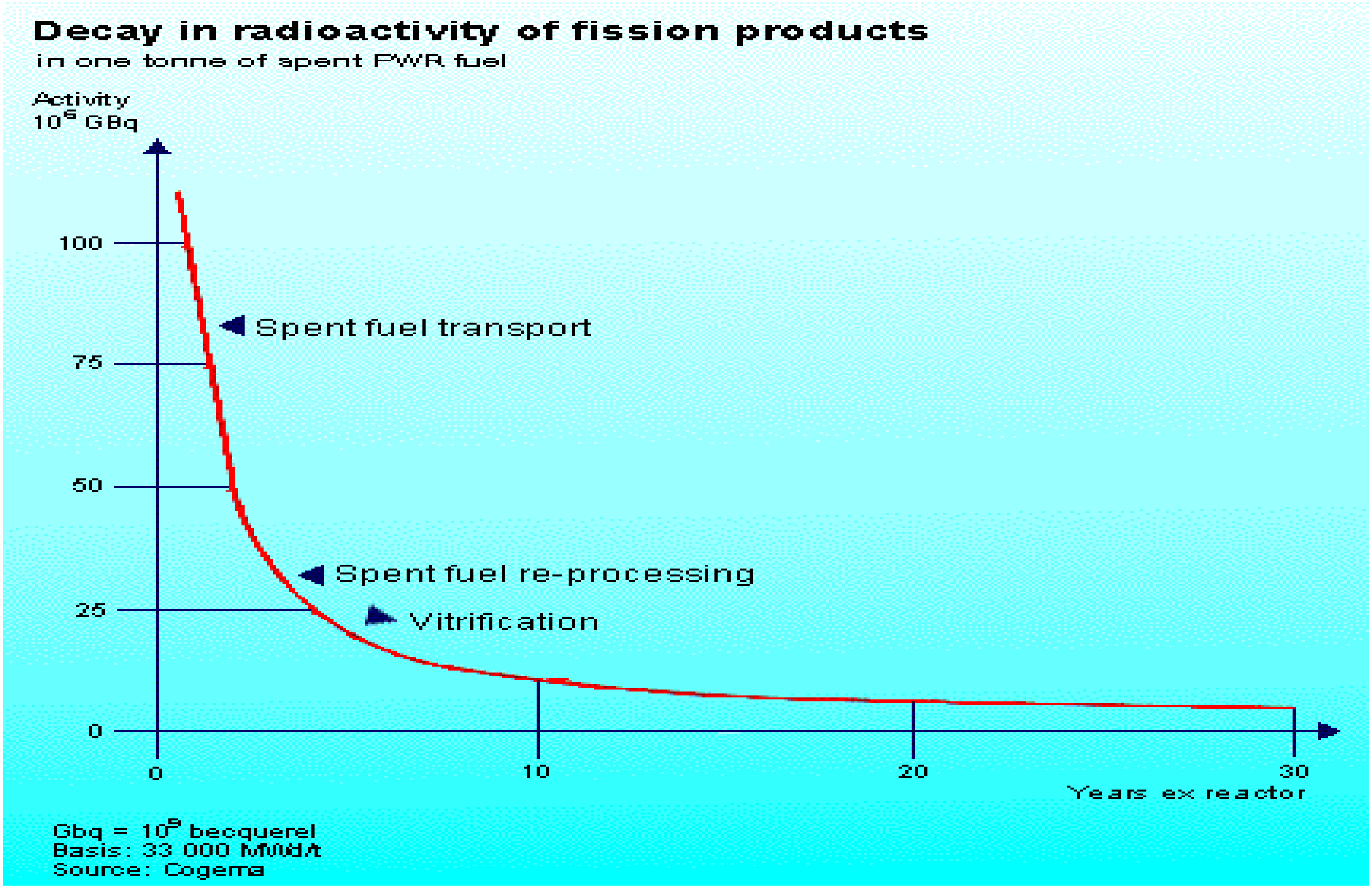
Used Fuel Resting Assembly



Storage Pond



Decay of Used Fuel



What to Do With Used Fuel

- The longer it is stored, the easier it is to handle, due to decay of radioactivity.
- There are two alternatives for used fuel

1) reprocessing to recover and recycle the usable portion of it

2) long-term storage and final disposal without reprocessing.

Reprocessing of Used Fuel

- Used fuel still contains about 96% of its original uranium, of which the fissionable U-235 content has been reduced to less than 1%. About 3% of the used fuel comprises waste products and the remaining 1% is plutonium (Pu) produced while the fuel was in the reactor and not 'burned' then.
- Reprocessing separates uranium and plutonium from waste products (and from the fuel assembly cladding) by chopping up the fuel rods and dissolving them in acid to separate the various materials.
- The remaining 3% of high-level radioactive wastes (some 750 kg per year from a 1000 MWe reactor) can be stored in liquid form and subsequently solidified.

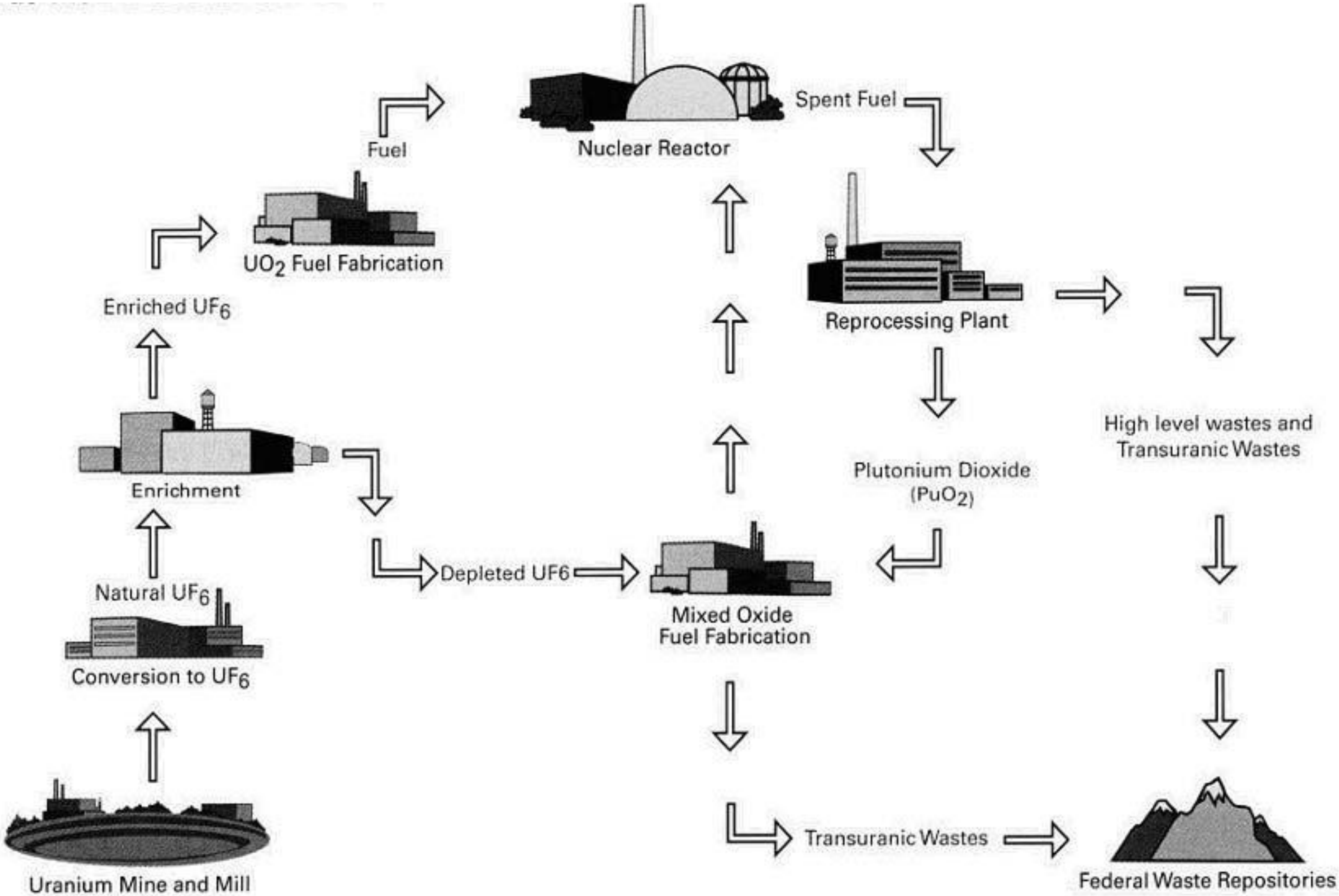
Why to Reprocess Nuclear Fuel

- Over the last 50 years the principal reason for reprocessing used fuel has been to recover unused uranium and plutonium in the used fuel elements and thereby close the fuel cycle, gaining some 25% to 30% more energy from the original uranium in the process and thus contributing to energy security.
- A secondary reason is to reduce the volume of material to be disposed of as high-level waste to about one fifth. In addition, the level of radioactivity in the waste from reprocessing is much smaller and after about 100 years falls much more rapidly than in used fuel itself.

Nuclear Recycling

- The uranium recovered from reprocessing, which typically contains a slightly higher concentration of U-235 than occurs in nature, can be reused as fuel after conversion and enrichment.
- The plutonium can be directly made into mixed oxide (MOX) fuel, in which uranium and plutonium oxides are combined. In reactors that use MOX fuel, plutonium substitutes for the U-235 in normal uranium oxide fuel

Nuclear Reprocessing



Nuclear Waste Categorization

- Wastes from the nuclear fuel cycle are categorised as high-, medium- or low-level wastes by the amount of radiation that they emit. These wastes come from a number of sources and include:

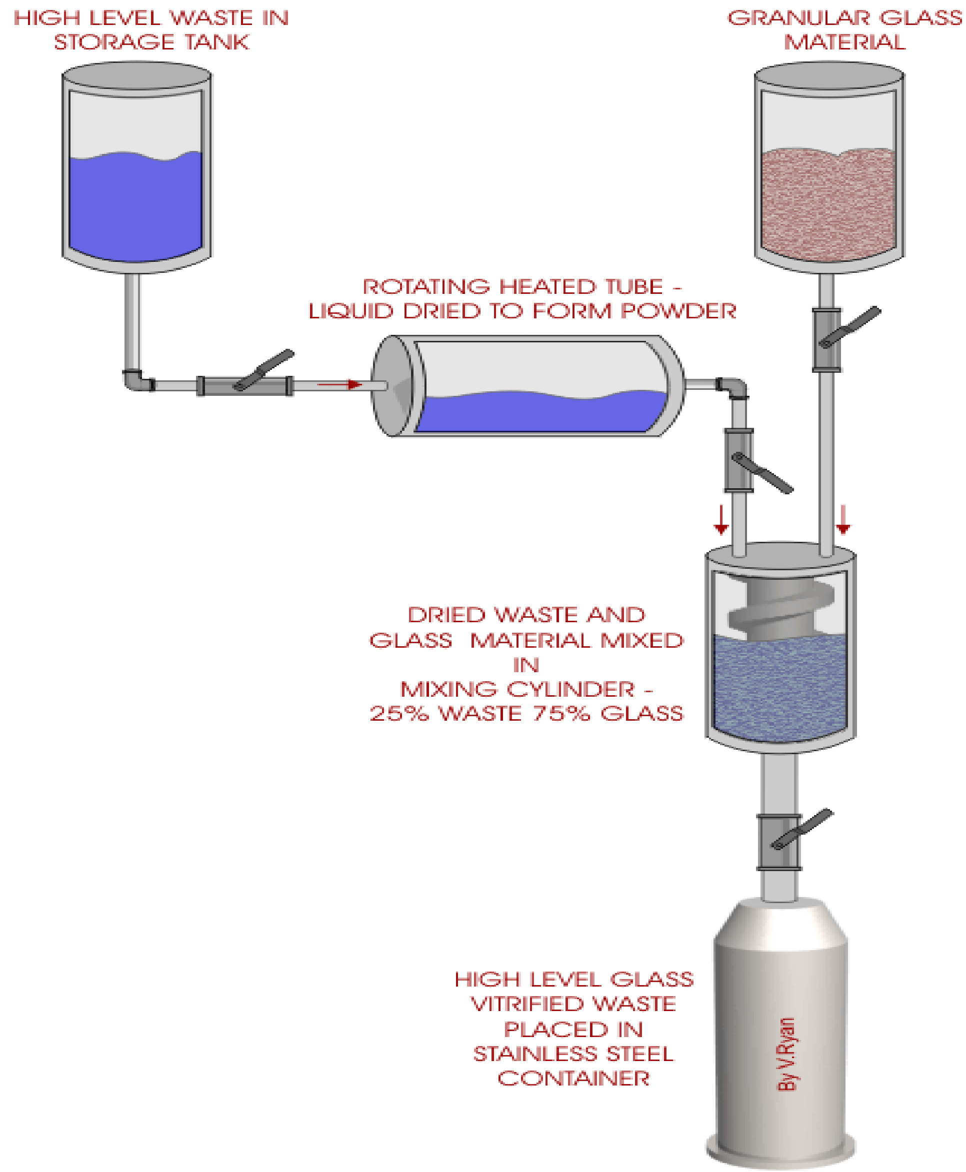
- low-level waste produced at all stages of the fuel cycle;
- intermediate-level waste produced during reactor operation and by reprocessing;
- high-level waste, which is waste containing the highly-radioactive fission products separated in reprocessing, and in many countries, the used fuel itself. Separated high-level wastes also contain long-lived transuranic elements.

How Much Waste is Produced

- Each year, nuclear power generation facilities worldwide produce about 200,000 m^3 of low- and intermediate-level radioactive waste, and about 10,000 m^3 of high-level waste including used fuel designated as waste
- In the OECD countries, **some 300 million tonnes of toxic wastes are produced each year**, but conditioned radioactive wastes amount to only 81,000 m^3 per year.
- **A typical 1000 MWe light water reactor will generate** (directly and indirectly**) 200-350 m^3 low- and intermediate-level waste per year**.

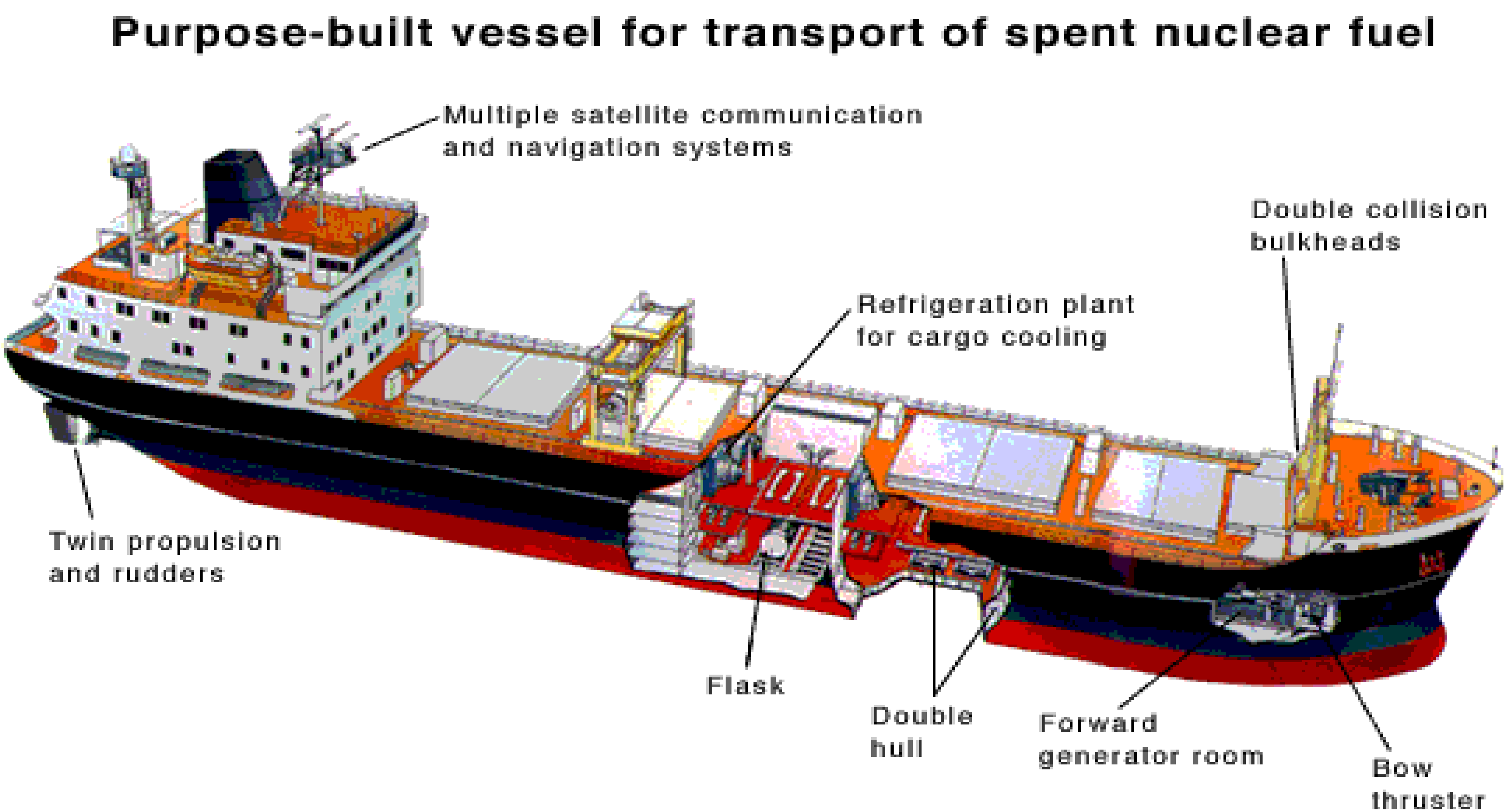
Nuclear Waste Processing-Vitrification

- After reprocessing, the liquid high-level waste can be calcined (heated strongly) to produce a dry powder which is incorporated into borosilicate (Pyrex) glass to immobilise it. The glass is then poured into stainless steel canisters, ***each holding 400 kg of glass.***
- **<u>A year's waste from a 1000 MWe reactor is contained in five tonnes of such glass, or about 12 canisters 1.3 metres high and 0.4 metres in diameter.</u>** These can readily be transported and stored, with appropriate shielding



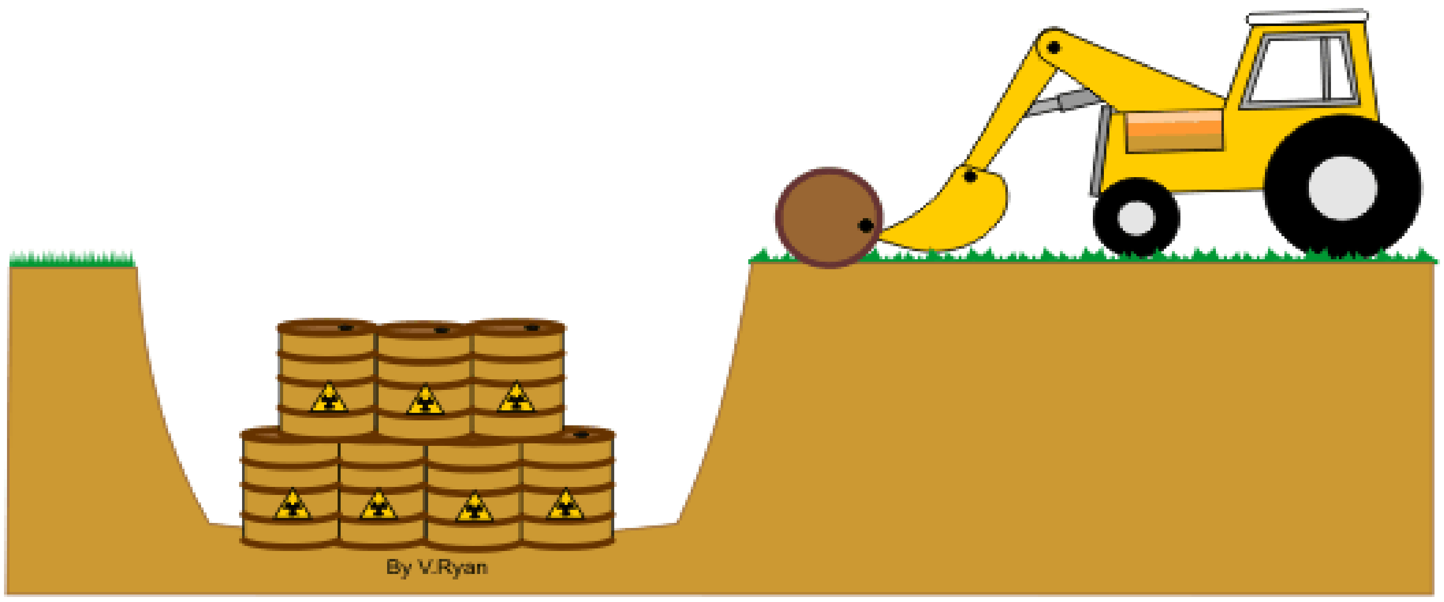
Nuclear Waste Transport

- Nuclear waste is usually transported with ships or with special trucks.



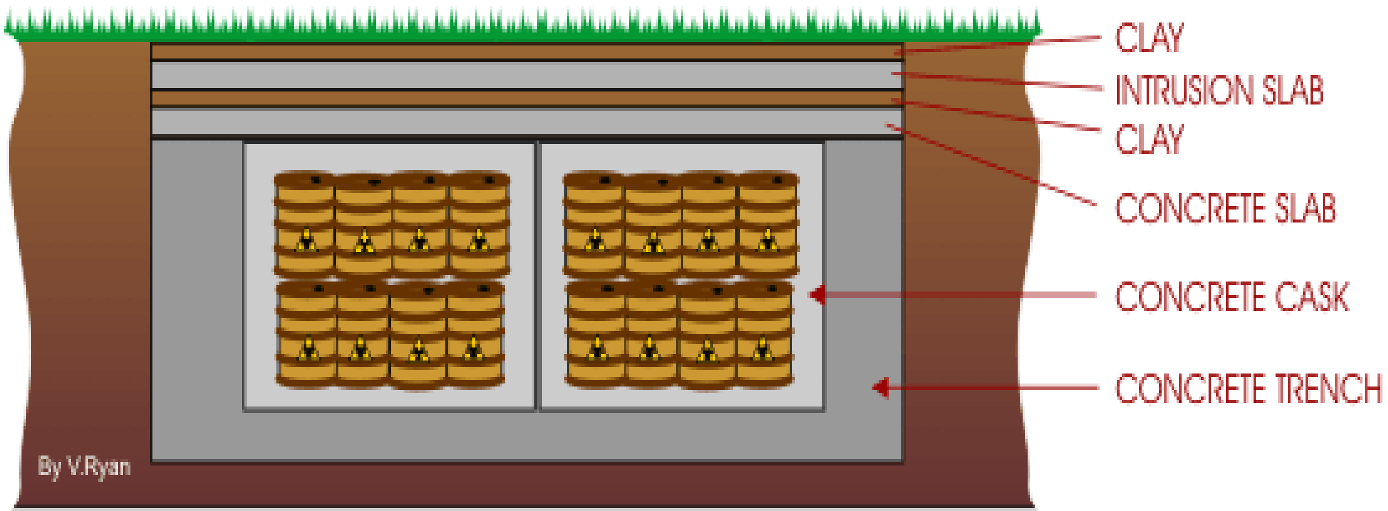
Nuclear Waste Handling & Transport

- Its essential to handle nuclear waste with care and it needs to be stored in proper repositories.



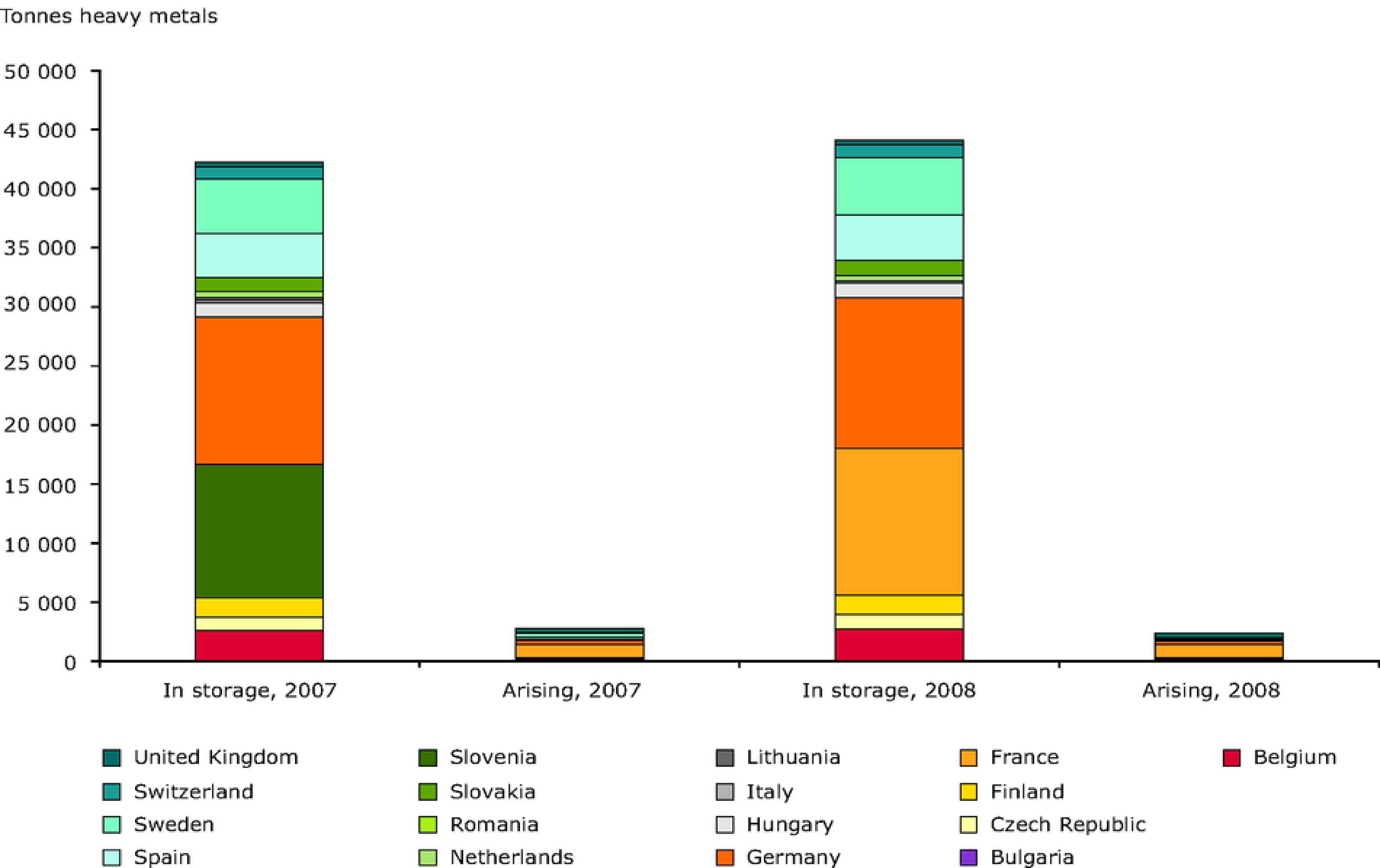
Nuclear Waste Storage

- For disposal, to ensure that no significant environmental releases occur over tens of thousands of years, 'multiple barrier' geological disposal is planned. This immobilises the radioactive elements in HLW and some ILW and isolates them from the biosphere. The main barriers are:
- Immobilise waste in an insoluble matrix such as borosilicate glass or synthetic rock (fuel pellets are already a very stable ceramic: UO2).
- Seal it inside a corrosion-resistant container, such as stainless steel.
- Locate it deep underground in a stable rock structure.
- Surround containers with an impermeable backfill such as bentonite clay if the repository is wet.

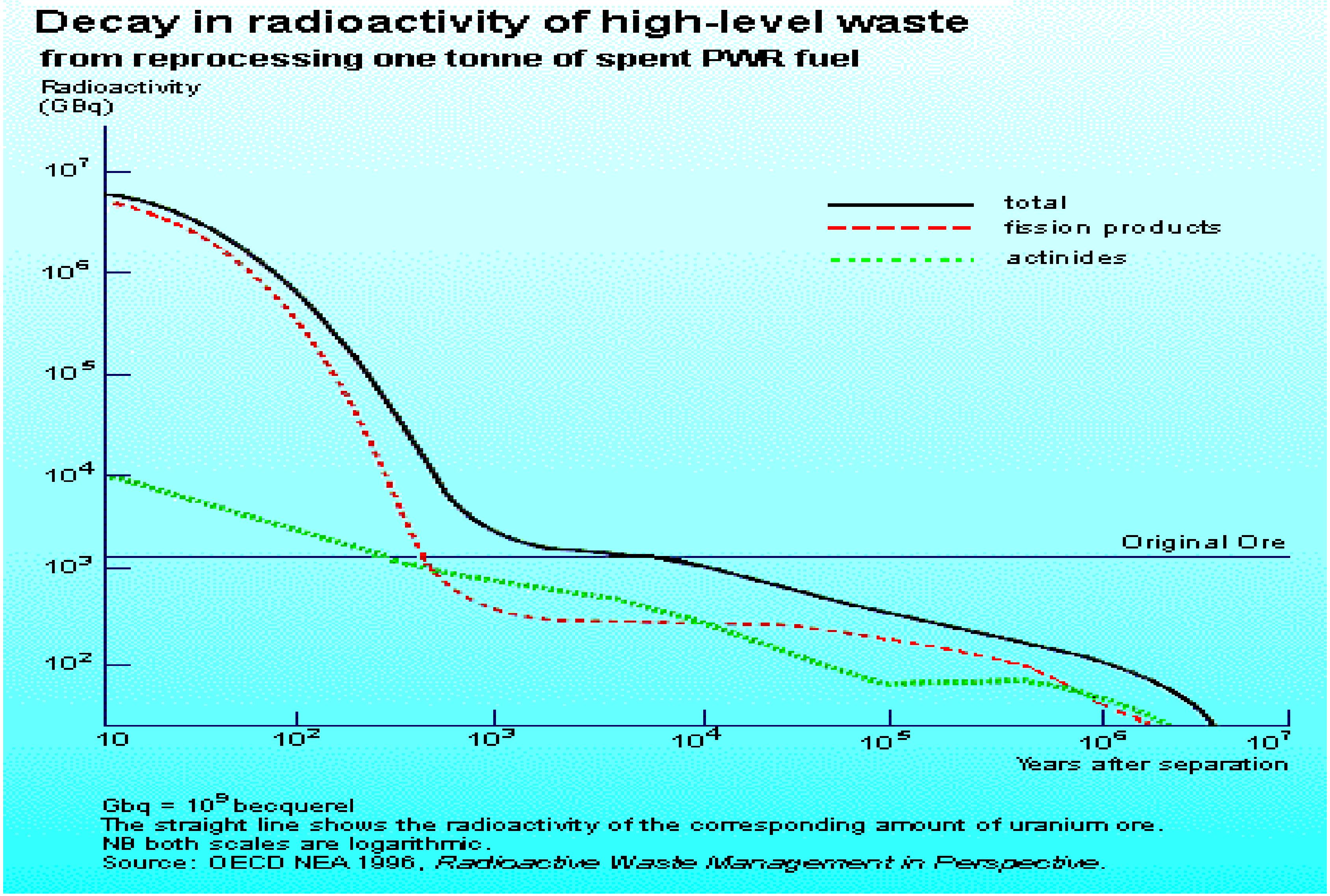


STORAGE OF INTERMEDIATE WASTE

European Nuclear Waste Storage



Decay Rate in Nuclear Waste



Repositories for Nuclear Waste

- The process of selecting appropriate deep geological repositories is now underway in several countries. Finland and Sweden are well advanced with plans for direct disposal of used fuel, since their parliaments decided to proceed on the basis that it was safe, using existing technology. Both countries have selected sites, in Sweden, after competition between two municipalities. The USA has opted for a final repository at Yucca Mountain in Nevada, though this is now stalled due to political decision

Nuclear Waste Storage

Disposal of Other Radioactive Wastes

- Some low-level liquid wastes from reprocessing plants are discharged to the sea. These include radionuclides which are distinctive, notably technetium-99 (sometimes used as a tracer in environmental studies), and this can be discerned many hundred kilometres away. However, such discharges are regulated and controlled, and the maximum radiation dose anyone receives from them is a small fraction of natural background radiation.

Cost of Radioactive Waste Management

- Financial provisions are made for managing all kinds of civilian radioactive waste. The cost of managing and **disposing of nuclear power plant wastes represents about 5% of the total cost of the electricity generated**.
- Most nuclear utilities are required by governments to put aside a levy (*e.g.* 0.1 cents per kilowatt hour in the USA, 0.14 ¢/kWh in France) to provide for management and disposal of their wastes . So far some **US$ 28 billion has been committed** to the US waste fund by electricity consumers.

World Situation in Radioactive Waste Management

- So far, almost 90,000 tonnes (of 290,000 t discharged) of used fuel from commercial power reactors has been reprocessed. Annual reprocessing capacity is now some 4000 tonnes per year for normal oxide fuels
- Between now and 2030 some 400,000 tonnes of used fuel is expected to be generated worldwide, including 60,000 t in North America and 69,000 t in Europe.

(tonnes per year)

LWR fuel	France, La Hague	1700	
	UK, Sellafield (THORP)	900	
	Russia, Ozersk (Mayak)	400	
	Japan (Rokkasho)	800*	
	Total LWR (approx)		3800
Other nuclear fuels	UK, Sellafield (Magnox)	1500	
	India (PHWR, 4 plants)	330	
	Total other (approx)		1830
Total civil capacity			5630

Material Balance in Nuclear Fuel Cycle

- The following figures may be regarded as typical for the annual operation of a 1000 MWe nuclear power reactor such as many operating today:

Mining	Anything from 20,000 to 400,000 tonnes of uranium ore
Milling	230 tonnes of uranium oxide concentrate (which contains 195 tonnes of uranium)
Conversion	288 tonnes uranium hexafluoride, UF_6 (with 195 tU)
Enrichment	35 tonnes enriched UF_6 (containing 24 t enriched U) – balance is 'tails'
Fuel fabrication	27 tonnes UO_2 (with 24 t enriched U)
Reactor operation	8760 million KWh (8.76 TWh) of electricity at full output, hence 22.3 tonnes of natural U per TWh
Used fuel	27 tonnes containing 240 kg transuranics (mainly plutonium), 23 t uranium (0.8% U-235), 1100 kg fission products.