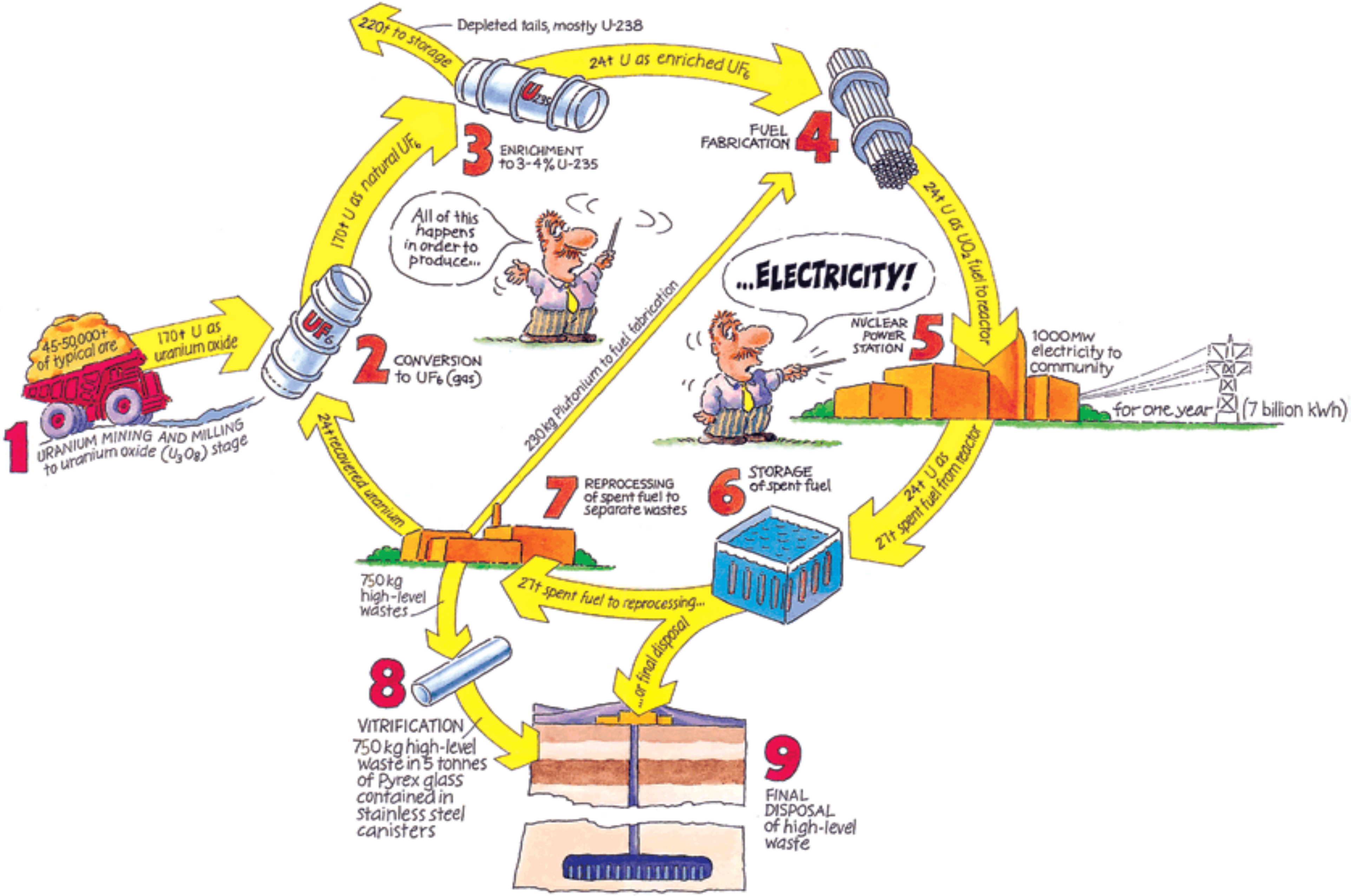
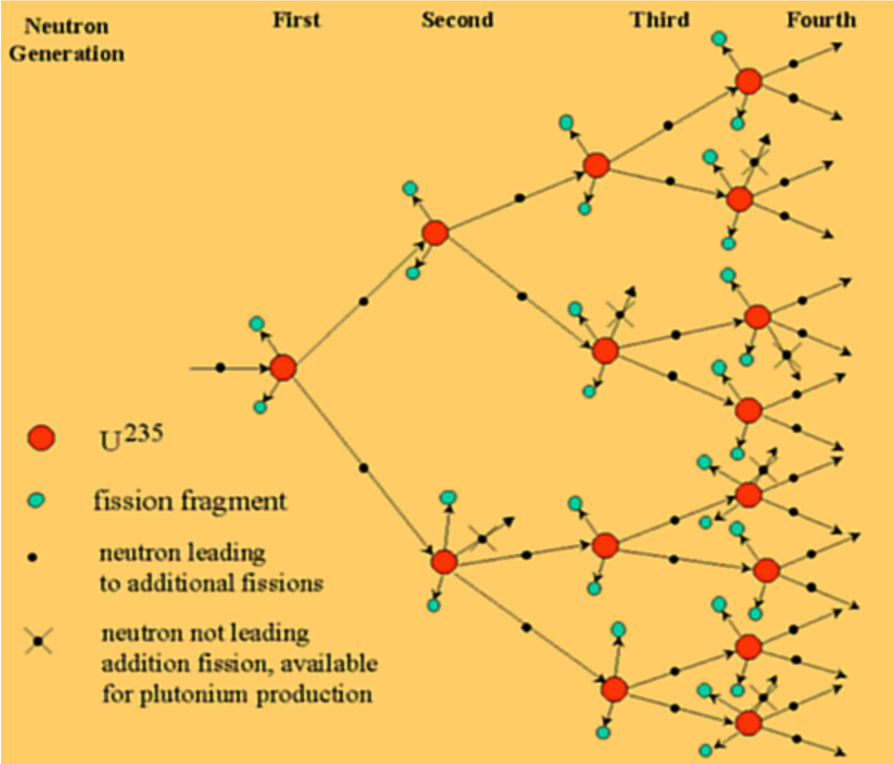
Mining, enrichment and fuel fabrication

Lecturer:
Associate professor Susanna Wold
School of Chemical Science and Engineering



Depleted tails, mostly U-238
220t to storage
24t U as enriched UF_6
3 ENRICHMENT to 3-4% U-235
FUEL FABRICATION 4
170t U as natural UF_6
All of this happens in order to produce...
...ELECTRICITY!
24t U as UO_2 fuel to reactor
45-50,000t of typical ore
170t U as uranium oxide
2 CONVERSION to UF_6 (gas)
230 kg Plutonium to fuel fabrication
NUCLEAR POWER STATION 5
1000MW electricity to community
for one year (7 billion kWh)
1 URANIUM MINING AND MILLING to uranium oxide (U_3O_8) stage
24t recovered uranium
7 REPROCESSING of spent fuel to separate wastes
6 STORAGE of spent fuel
24t U as 27t spent fuel from reactor
750 kg high-level wastes
27t spent fuel to reprocessing...
...or final disposal
8 VITRIFICATION
750 kg high-level waste in 5 tonnes of Pyrex glass contained in stainless steel canisters
9 FINAL DISPOSAL of high-level waste



By early 1942, it was known that the two naturally occurring isotopes of uranium reacted with neutrons as follows:

$$^{235}U_{92} + \ ^{1}n_{0} \ \text{-->} \ \text{fission products} + (2.5)^{1}n_{0} + 200 \text{ MeV Energy}$$

$$^{238}U_{92} + \ ^{1}n_{0} \ \text{-->} \ ^{239}U_{92}$$

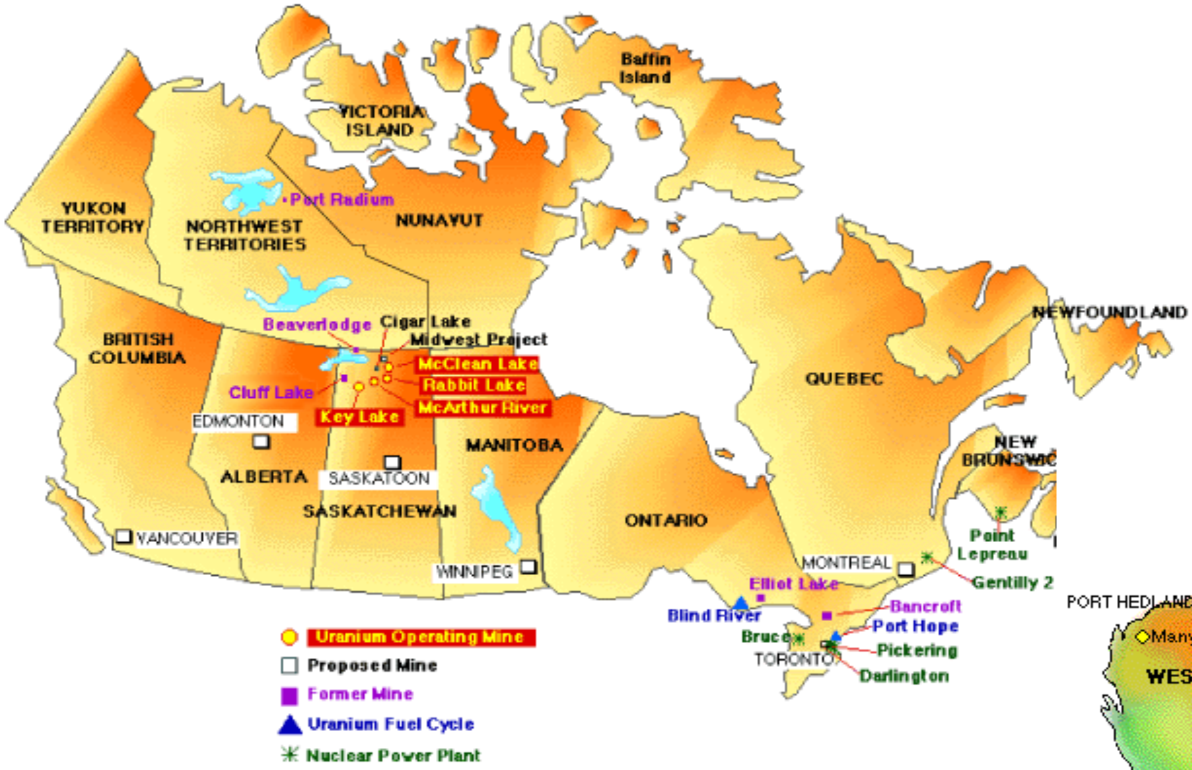
$$^{239}U_{92} \ \text{-->} \ ^{239}Np_{93} + \beta^{-1} \quad t_{1/2}=23.5 \text{ min.}$$

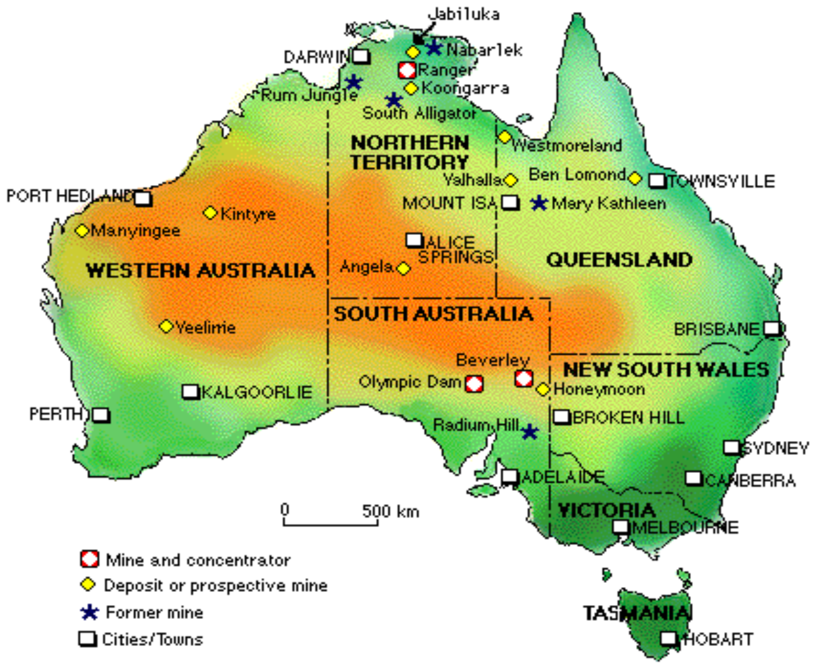
$$^{239}Np_{93} \ \text{--->} \ ^{239}Pu_{94} + \beta^{-1} \quad t_{1/2}=2.33 \text{ days}$$

Each U-235 that undergoes fission produces an average of 2.5 neutrons. In contrast, some U-238 nuclei capture neutrons, become U-239, and subsequently emit two beta particles to produce Pu-239. The plutonium was fissile also and would produce energy by the same mechanism as the uranium. A flow sheet for uranium fission is shown below.

Criticality: The key is to maintain a nuclear reaction within a nuclear reactor to use the neutrons being released during fission to stimulate fission in other nuclei. With careful control over the geometry and reaction rates, this can lead to a self-sustaining chain reaction, known as criticality.

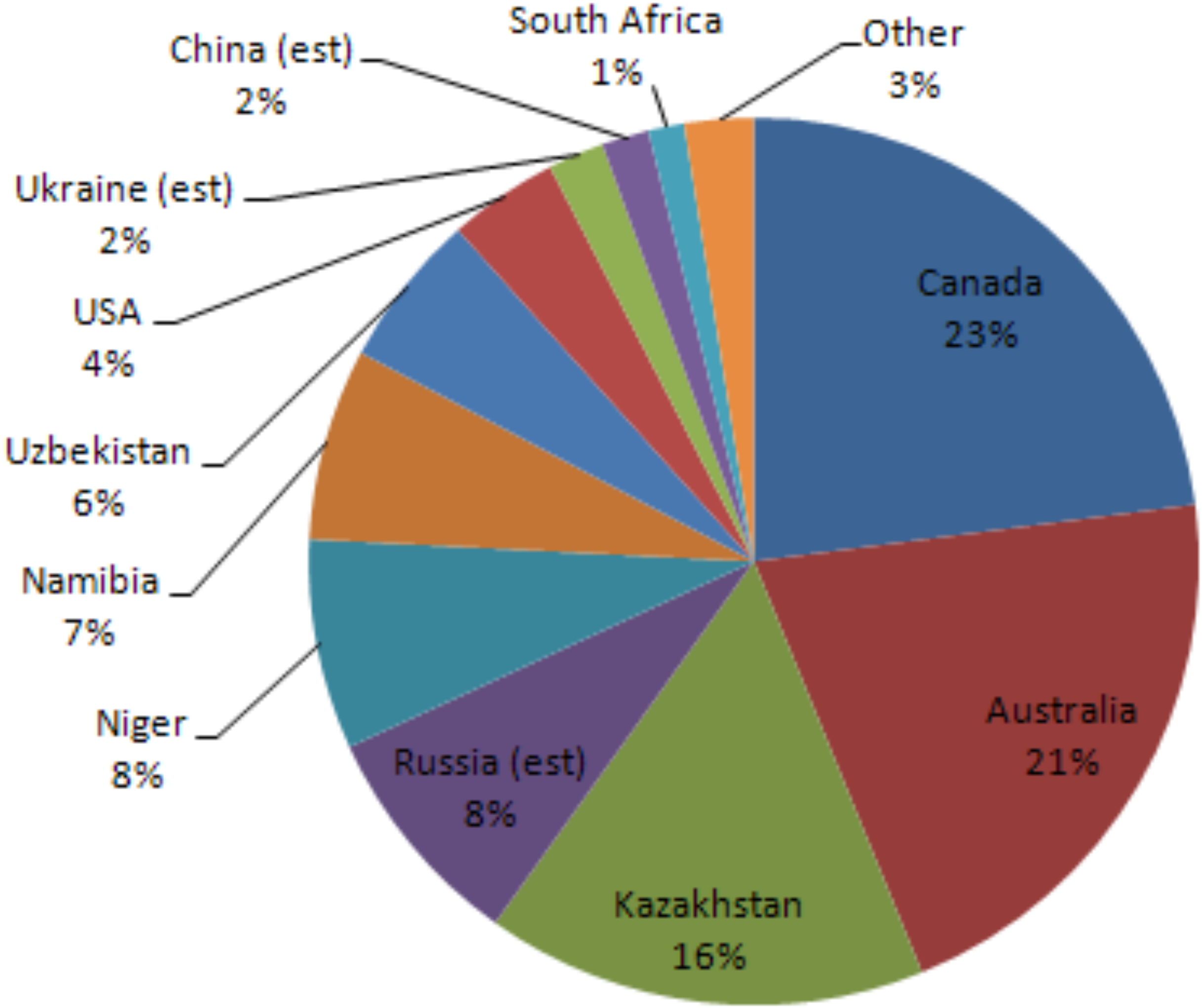
Mines and supply

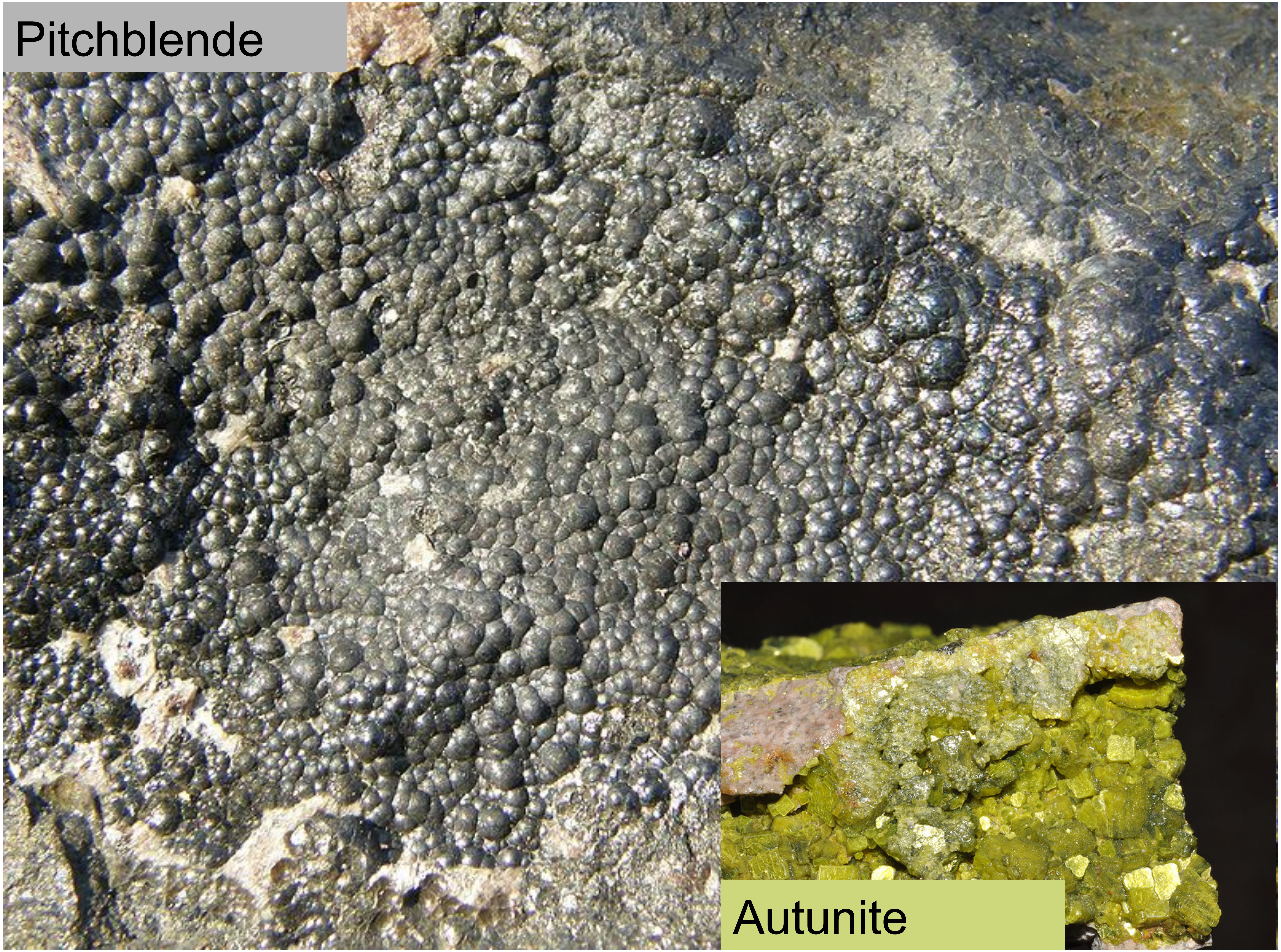




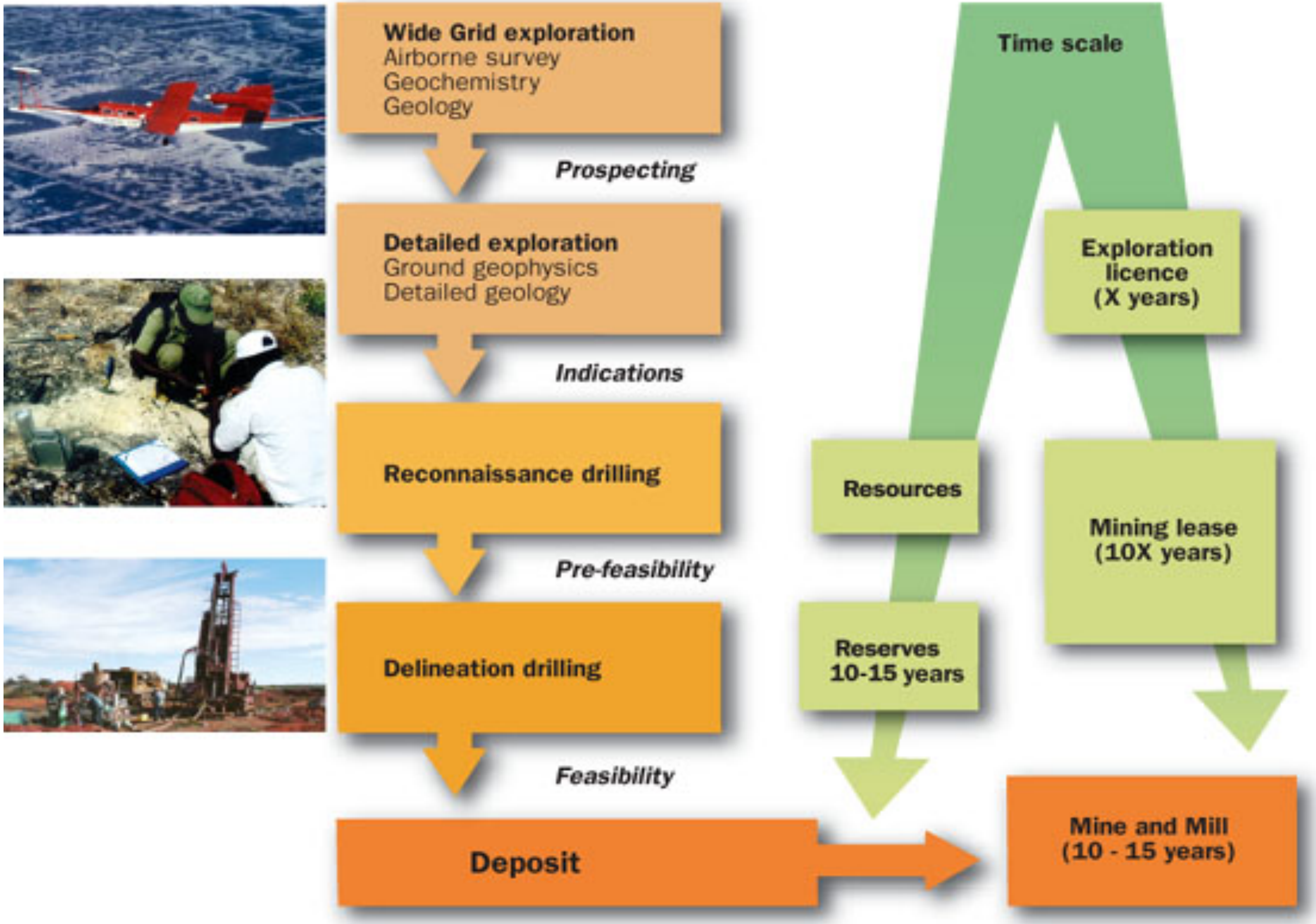
uraninite	UO_2
pitchblende	U_3O_8, rare U_3O_7
coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$
brannerite	UTi_2O_6
davidite	$(REE)(Y,U)(Ti,Fe^{3+})_{20}O_{38}$

2007 Uranium Mining




Pitchblende
Autunite

Extraction
Prospection



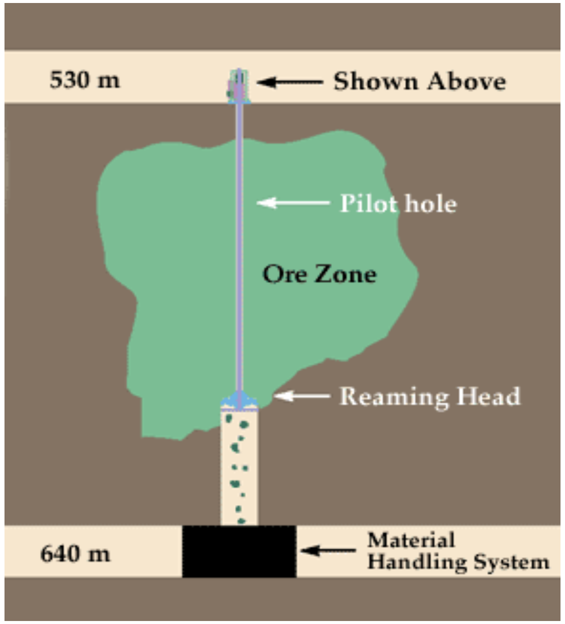
Open-pit mine

Less than 200 m depth and open to the surface

Extraction method similar to any other surface mine: drilling
blasting in benches

Hydraulic excavators load the broken ore into large trucks for transport to the crushing and milling plant.

Underground Mine



method used if the ore body is too deep to be extracted by open-pit

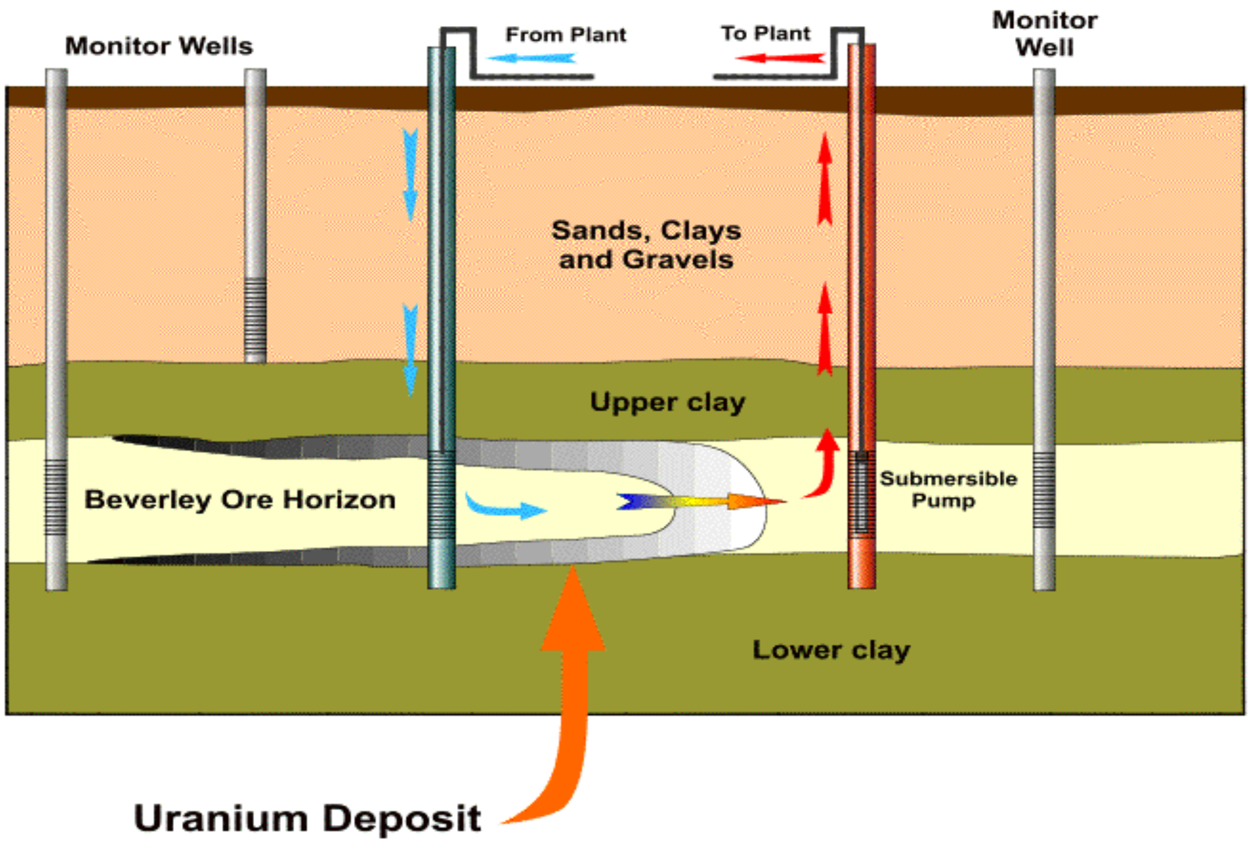
Other underground uranium mines at
Rabbit Lake in Canada. Akouta in Niger.

In-situ Leaching

Technology only suitable for permeable ore bodies such as sandstone-hosted deposits.

The host rock is relatively undisturbed and no large cavities are created.

In-situ Leaching



An alkaline or acid solution is injected into the ore body with an oxidant.

The uranium is dissolved into the solution and the U-pregnant fluid is pumped to the surface.

After the uranium has been removed from the solution, the fluid is re-injected into a closed circuit.

Solvent depends on?

In-situ leaching

Advantages

- cheaper infrastructure
- no large-scale tailings dams
- no large open cut or underground mine
- lower occupational health and safety : accidents, dust and radiation
- reduced workforce

Disadvantages

- significant risks of contaminating groundwater systems outside the mining zone.
- inherent difficulties in the hydraulic and geochemical behaviour of the deposit.
- difficult to restore groundwater to pre-mining quality.
- large volumes of waste water and solutions to dispose.

Environmental aspects: mining/ milling

Environmental aspects of a uranium mine: the same as those of other metal mining.

Radioactivity associated with the uranium ore requires some special management .

The uranium itself has a very low level of radioactivity, comparable with granite.

Waste from mining: tailings and radon

Tailings: solid waste products from the milling operation

tailings on the surface: measures taken to minimize the emission of radon gas.

During mining operation: material in the tailings dam usually covered by water to reduce surface radioactivity and radon emission.

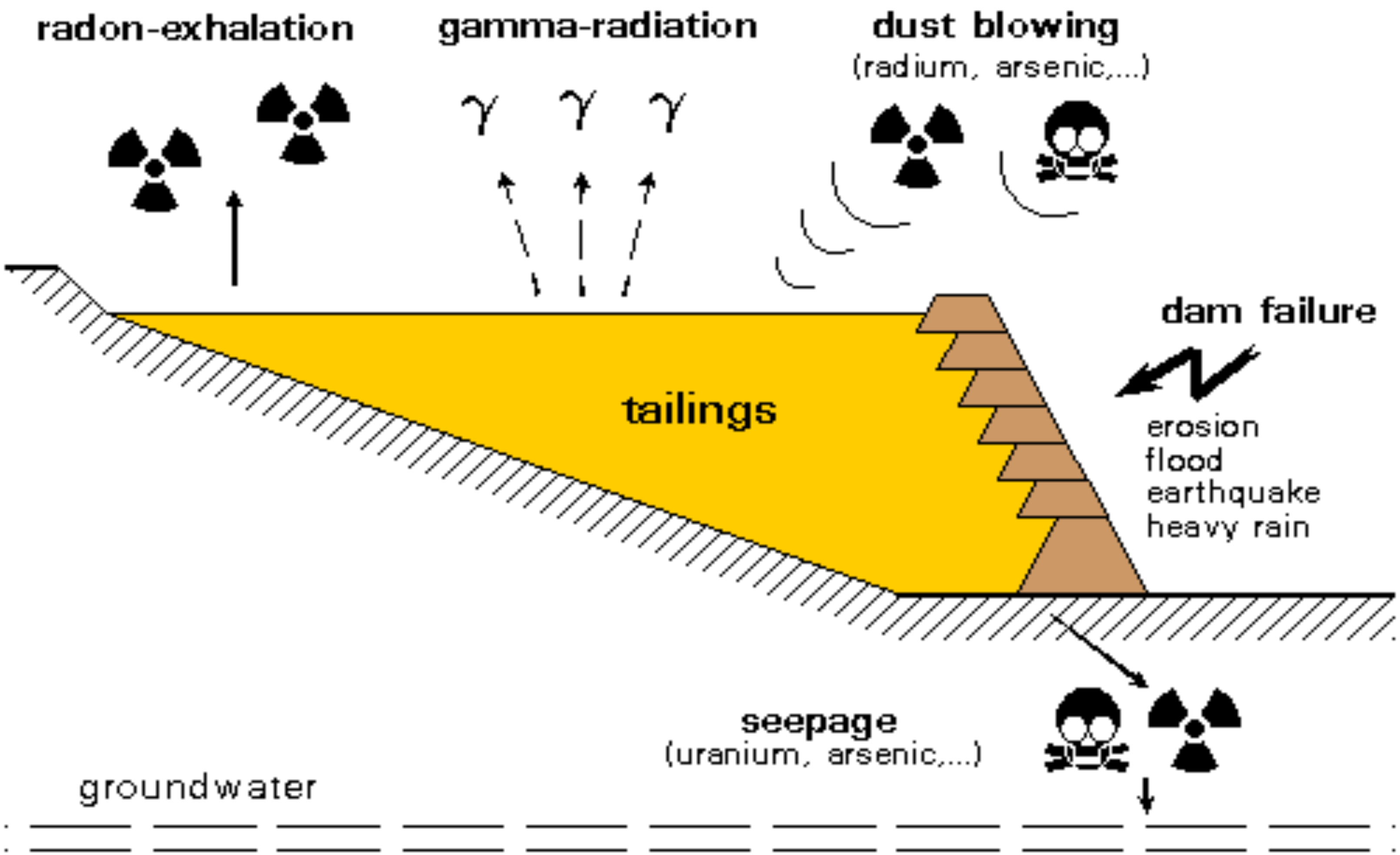
After: covered with two metres of clay and topsoil

Waste from mining: water

Run-off from the mine stockpiles and waste liquors from the milling operation collected in secure retention ponds.

- Isolation and recovery of any heavy metals or other contaminants.
- Natural evaporation or recirculation to the milling operation of the liquid portion.

Uranium Mill Tailings Hazards



Other U-sources

Co-product or By-product:

12% of uranium mined recovered from copper or gold mining operations in 2004.

Example: Olympic Dam (South Australia)

Treatment of the ore in a copper sulphide flotation plant to remove copper.

Approximately 80% of the uranium remains in the tailings from the flotation cells and is recovered by acid leaching.

The copper concentrate is also processed through an acid leach to remove any remaining uranium.

Other U-sources

Recovery from seawater

Uranium concentration of sea water: 3.3 mg/m^3 but quantity of this resource is gigantic (4.5 billion tons)

Research and development for recovery of this low-concentration element
by inorganic adsorbents such as titanium oxide compounds
low recovery efficiency

In Japan: research and development of the production of adsorbent by irradiation of polymer fiber.

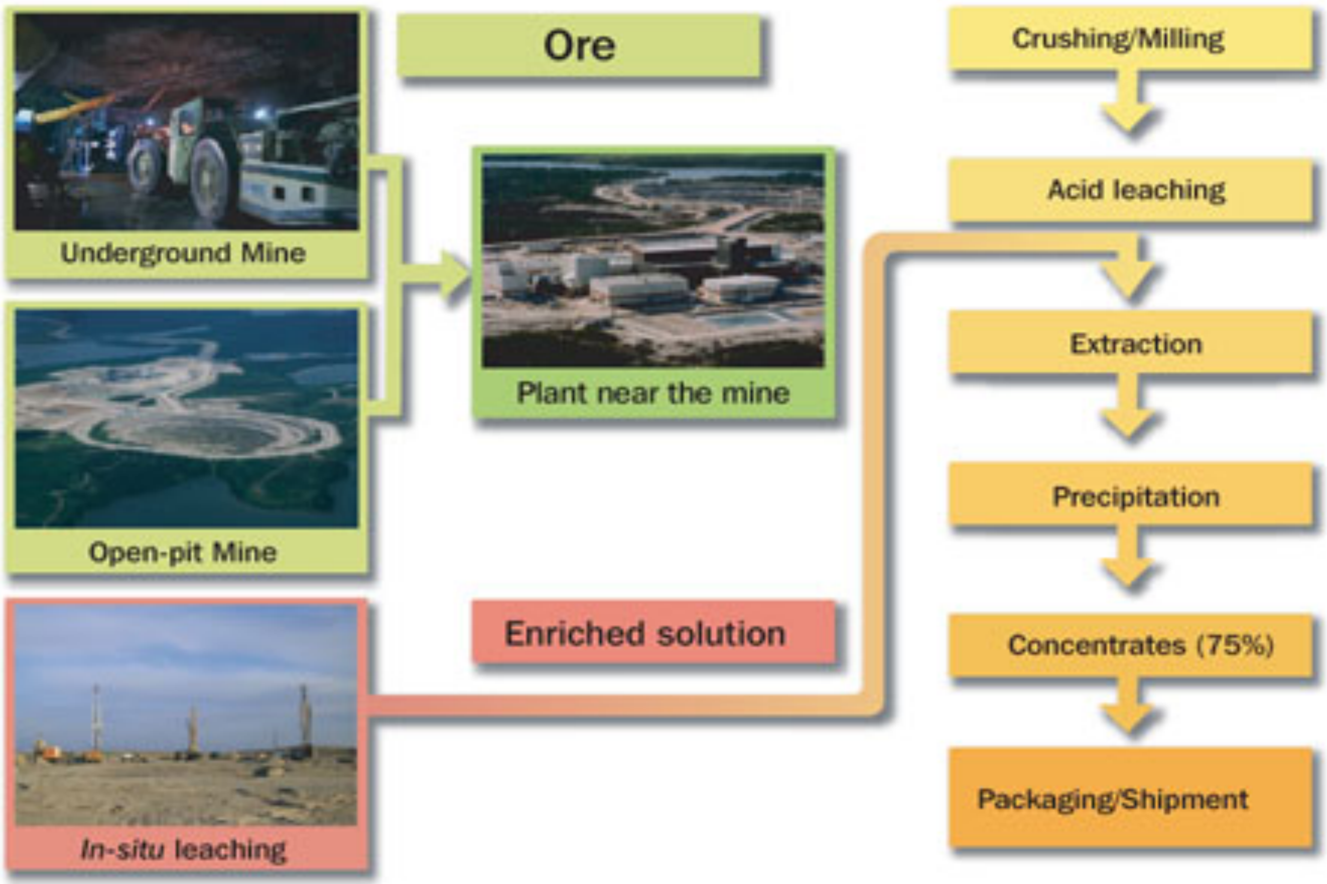
Uranium adsorption capacity of the polymer fiber adsorbent is 10x greater than
the titanium oxide adsorbent.

If Uranium mineral deplete, maybe economy in this.

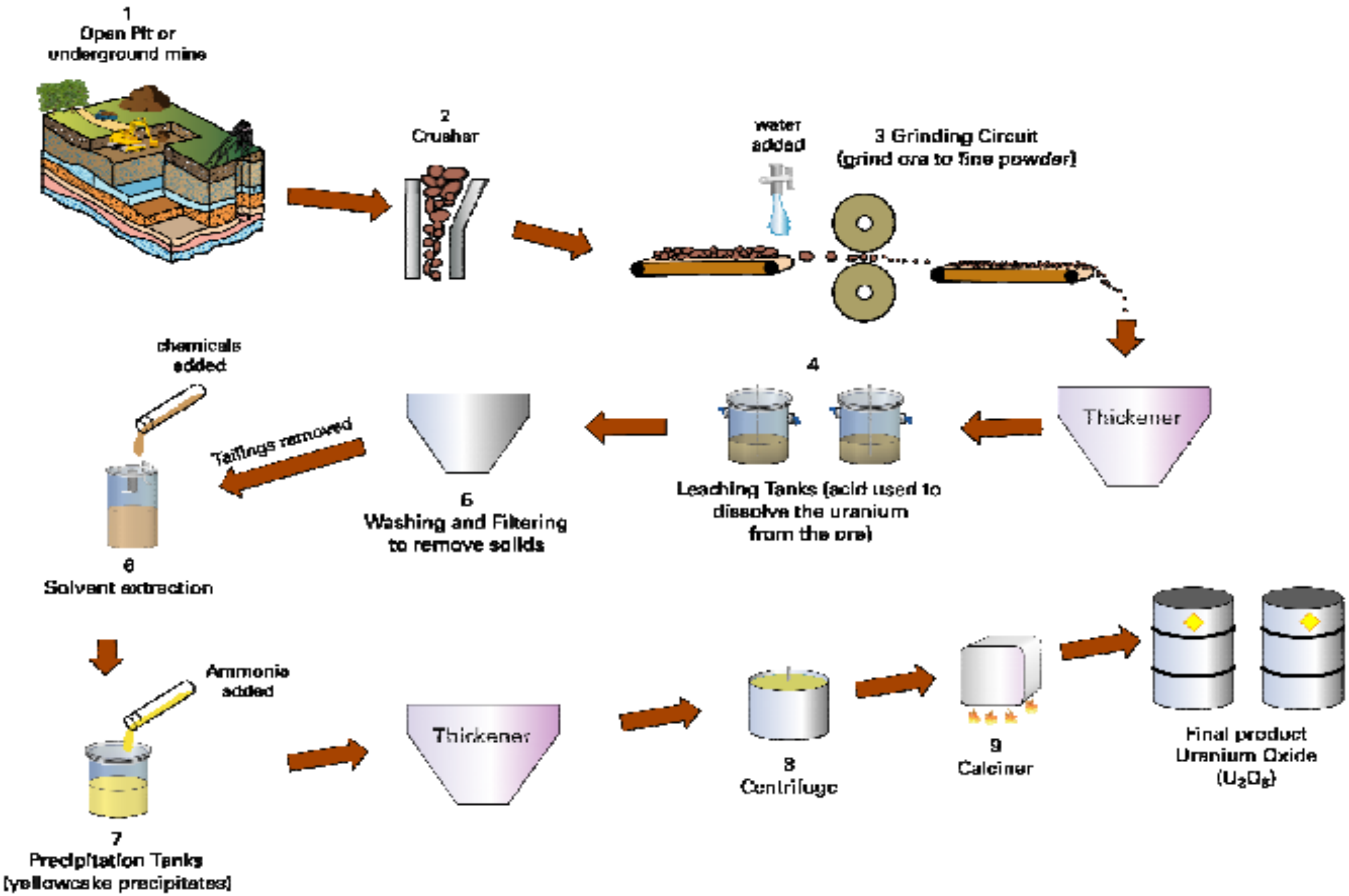
Extraction and conversion of uranium

From ore to UF_6

Extraction


Ore
Crushing/Milling
Underground Mine
Plant near the mine
Acid leaching
Extraction
Open-pit Mine
Precipitation
Enriched solution
Concentrates (75%)
In-situ leaching
Packaging/Shipment

Processing: from ore to U_3O_8 (yellowcake)



Conversion: from U_3O_8 to UF_6

Why?

- The enrichment process requires the uranium to be purified and then converted to a gas, uranium hexafluoride.
- Can be handled at reasonable temperatures at atmospheric pressure (solid<57°C<gas).
- Is water soluble.

Where?

9 plants operating the conversion process:

France (x 2), Russia (x 2), USA, Canada, UK, China and Argentina.

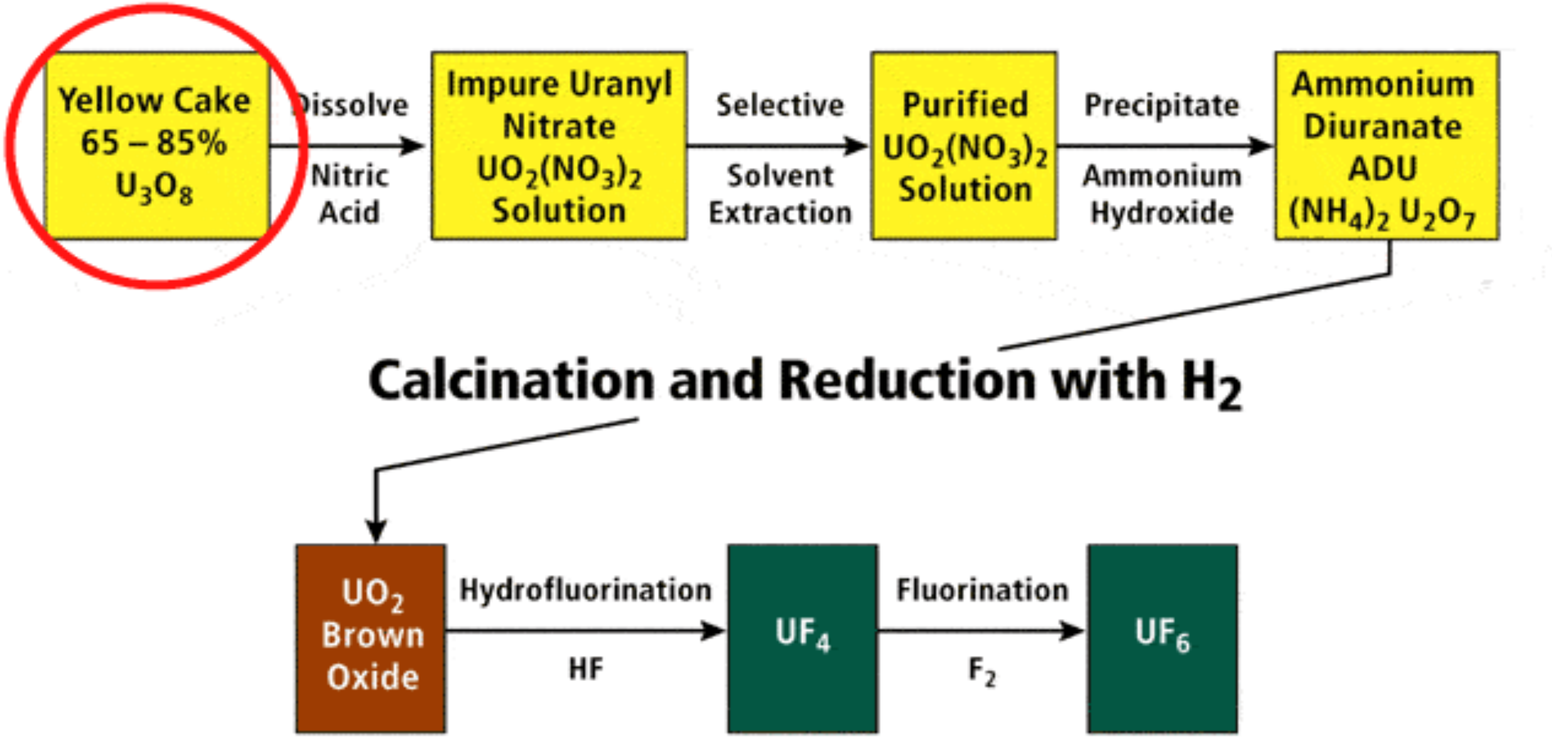
Chemical forms of uranium during conversion:

yellowcake

uranyl nitrate solution [$UO_2(NO_3)_2$]

solid ammonium diuranate [$(NH_4)_2U_2O_7$]

Conversion



Yellow cake is converted to uranium hexafluoride through a multi-step chemical process using nitric acid, ammonium hydroxide, hydrogen, hydrofluoric acid (HF) and fluorine (F_2).

Uranium hexafluoride [UF_6] is a white crystalline solid that resembles rock salt. It is then transferred to the enrichment plant in solid form in pressurized containers.

Natural isotopic mix of U:
0.72 % ^{235}U and 99,3 % ^{238}U 0.005% ^{234}U

Some reactors can take this mix as some heavy-water reactors as CANDU and British gas cooled graphite moderated Magnox reactors

Most of reactors need higher amount of ^{235}U between 2-5 %

No amount of ^{238}U can be made "critical", however, since it will tend to parasitically absorb more neutrons than it releases by the fission process. ^{235}U on the other hand, can support a self-sustained chain reaction, but due to the low natural abundance of

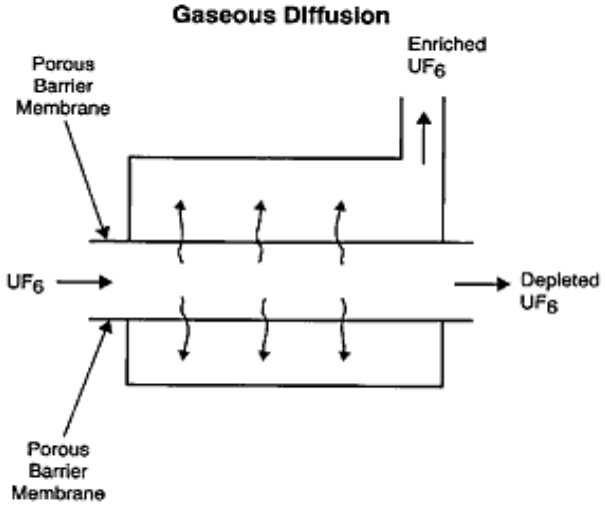
^{235}U, natural uranium cannot achieve criticality by itself.

Methods of isotopic enrichment

Using the isotopic mass differences

1. Gaseous diffusion
2. Gaseous centrifugation
3. Aerodynamic methods
4. Laser methods
5. Chemical separation methods
6. Electromagnetic separators

Gaseous diffusion



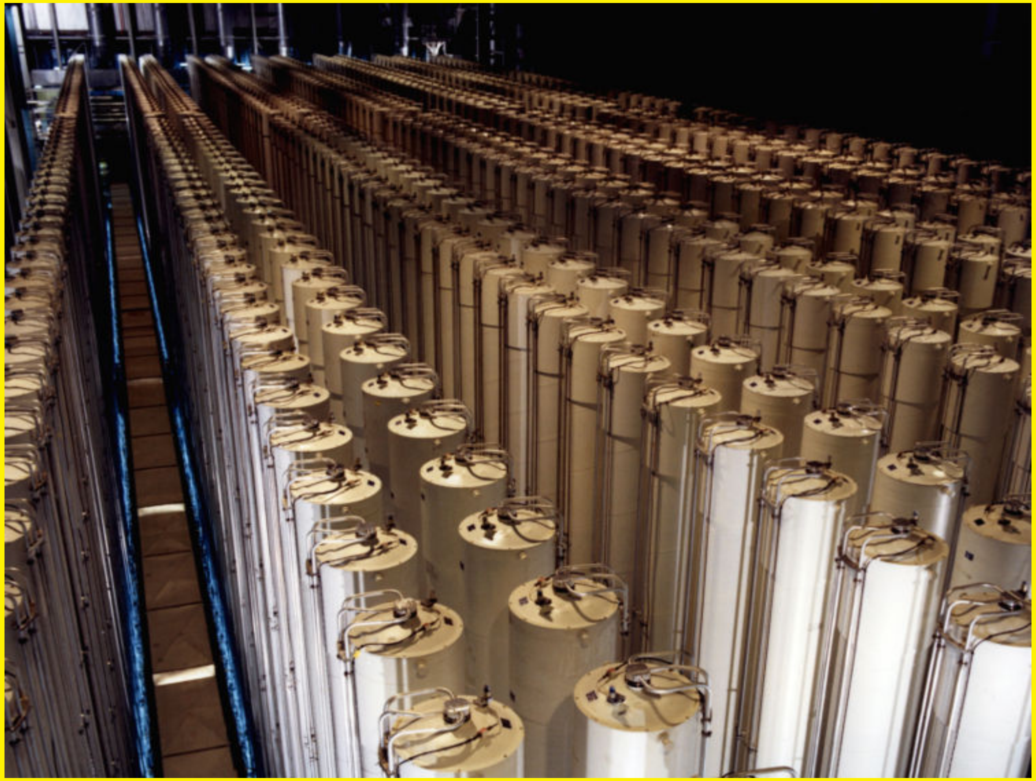
Gaseous diffusion is a technology used to produce enriched uranium by forcing gaseous uranium hexafluoride (Hex) through semi-permeable membranes. This produces a slight separation between the molecules containing ^{235}U and ^{238}U since ^{235}U is lighter than ^{238}U . Lighter molecules will hit the walls of the gas containing vessel more often than the heavier ones. Replacing the opaque wall with a semi-permeable membrane with holes big enough that single molecules can excape but small enough not to allow forming of continous gas stream leaks, the forming gas behind the the membrane will contain higher ratio of lighter molecules than the original gas.

Practically serveral thousands of separation units are stacked one after another in order to reach the needed level of enrichment.

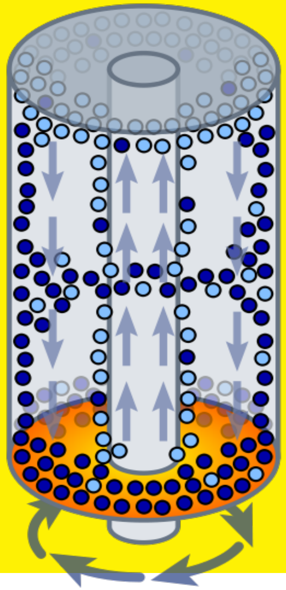
Energy needs of diffusion enrichment plants are very high. Now it is forced aside by gaseous centrifugation since it is so economical and energetically demanding.

Gaseous centrifugation

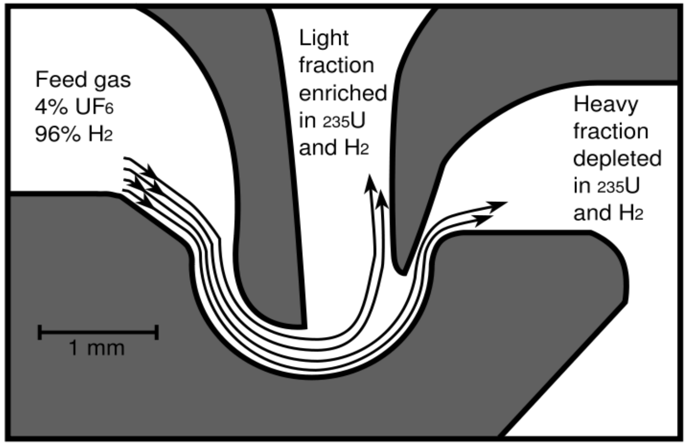
The gas centrifuge process uses a large number of rotating cylinders in series and parallel formations.
This rotation creates a strong centrifugal force so that the heavier gas molecules containing 238U move toward the outside of the cylinder and the lighter gas molecules rich in 235U collect closer to the center.
It requires far less energy to achieve the same separation than the older gaseous diffusion process, which it has largely replaced



A cascade of gas centrifuges at a U.S. enrichment plant



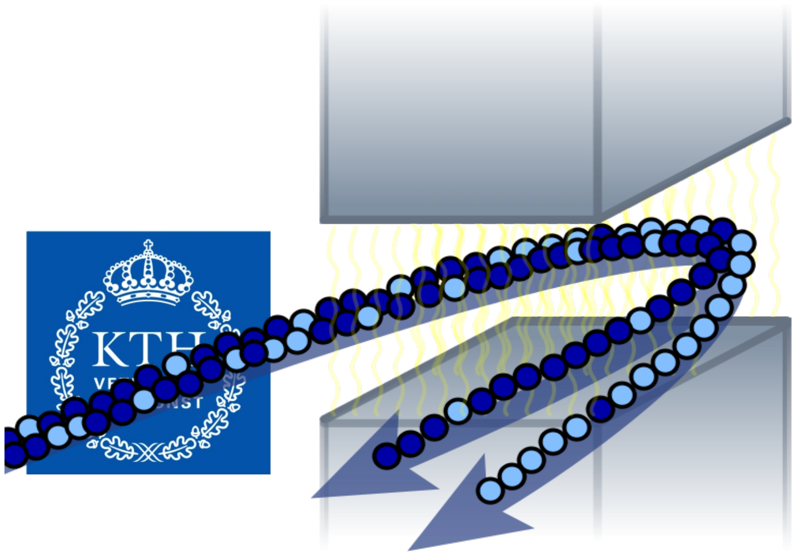
Aerodynamic methods



Aerodynamic methods use physical isotope effect occuring under conditions of high linear and radial acceleration for isotopic separation. Such accelerations are created while pumping gaseous isotopic mixture through a curved slit during supersonic expansion. As a result of diffusion and centrifugal effect combination, the inner part of the gas cluster is enriched by the lighter fraction while the covering part concentrates the heavier component. Inserting a slide separating the two parts leads to their seperation.

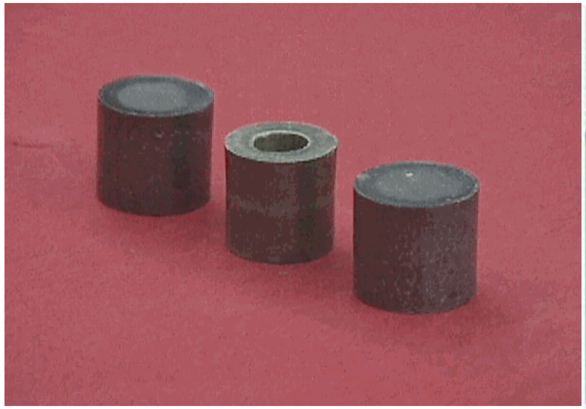
Smaller separation efficiency than for the centrifugation method and energy needs comparable with diffusion method had obstructed wider industrial application of these methods.

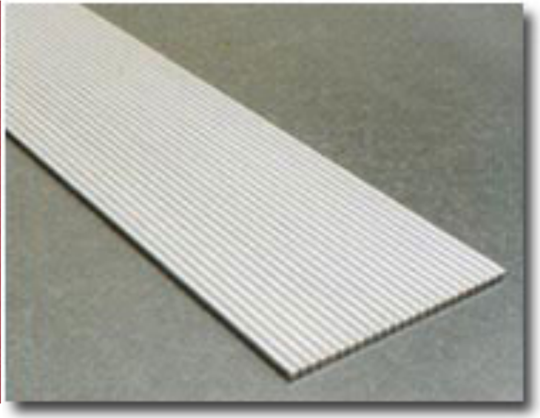
Electromagnetic isotope separation



Electromagnetic isotope separation process (EMIS). In the electromagnetic separation process, the metallic uranium is first vaporized, and then ionized to positively charged ions. The cations are then accelerated and subsequently deflected by magnetic fields onto their respective collection targets. A production-scale mass spectrometer named the Calutron was developed during World War II that provided some of the 235U used for the Little Boy nuclear bomb, which was dropped over Hiroshima in 1945. Properly the term 'Calutron' applies to a multistage device arranged in a large oval around a powerful electromagnet. Electromagnetic isotope separation has been largely abandoned in favour of more effective methods.

Preparation of fuel





Manufacturing process of UO_2 pellets: Usual conversion process

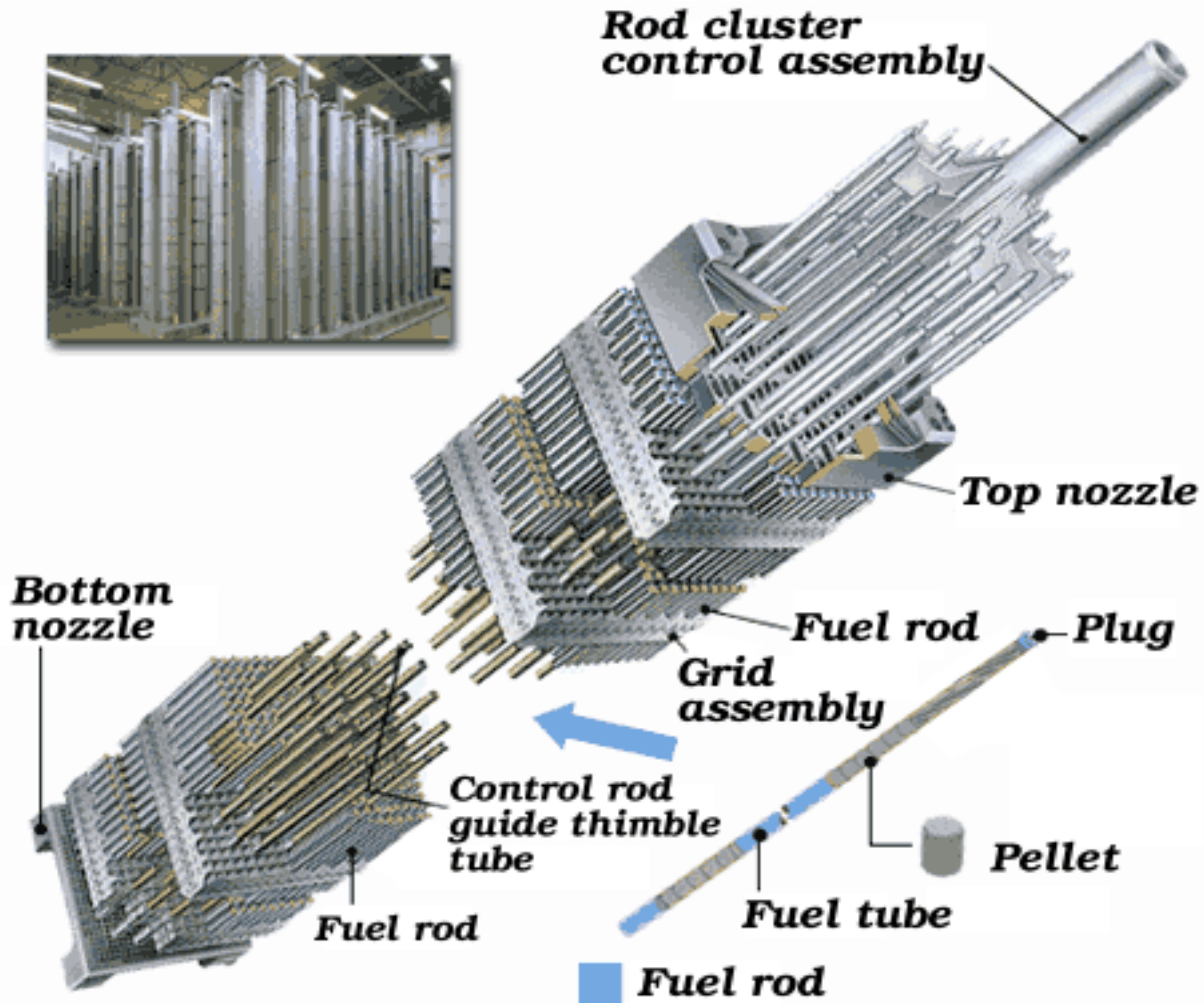
UF_6 (powder) → UF_6(gas) → UO_2F_2(liq) → ADU(sol) → UO_2

- vaporisation (UF_6 (powder) → UF_6(gas))
- absorption by pure water (UF_6(gas) → UO_2F_2(liq))
- addition of ammonium hydroxide (UO_2F_2(liq) → ADU(sol))
- dewatering, drying, calcinations, reduction, milling (ADU(sol) → UO_2)

Manufacturing process of UO_2 pellets: The Integrated Dry Route

UF_6 is converted into a ceramic grade uranium dioxide powder, in a single stage.

Manufacturing process of UO_2 pellets: Fuel assembly manufacturing



Manufacturing process of UO_2 pellets: fuel rod manufacturing

UO_2 pellets are loaded into a tube.

The metal used for the tubes depends on the design of the reactor. (Stainless steel, Zirconium)

Top and bottom end plugs are alternately welded to the fuel tube.

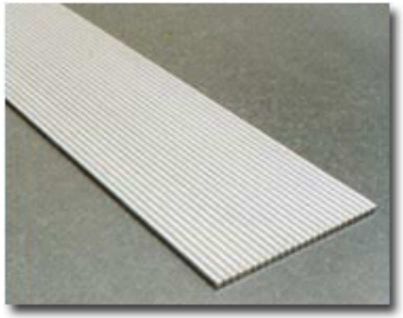
Helium gas is pressurized through a vent hole in the top end plug and the vent hole is then seal-welded.

Thus, a four meter length fuel rod is produced.

Manufacturing process of UO_2 pellets

UO_2 powder

UO_2 pellets



Fuel rods

Fuel assembly

Manufacturing process of UO_2 pellets: Fuel assembly manufacturing

A typical large pressurized water reactor contains 193 fuel assemblies composed of about 51,000 fuel rods containing more than 18 million uranium dioxide fuel pellets.

A fuel assembly's life in a reactor is 36 to 54 months, after which the chain reaction's efficiency begins to decrease. Operators then remove the fuel from the reactor through refueling every 18 to 24 months. At that time, operators replace about one-quarter to one-third of the fuel assemblies with new fuel.