MEEN 40090: Energy Systems & Climate Change
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Nuclear Energy (2)

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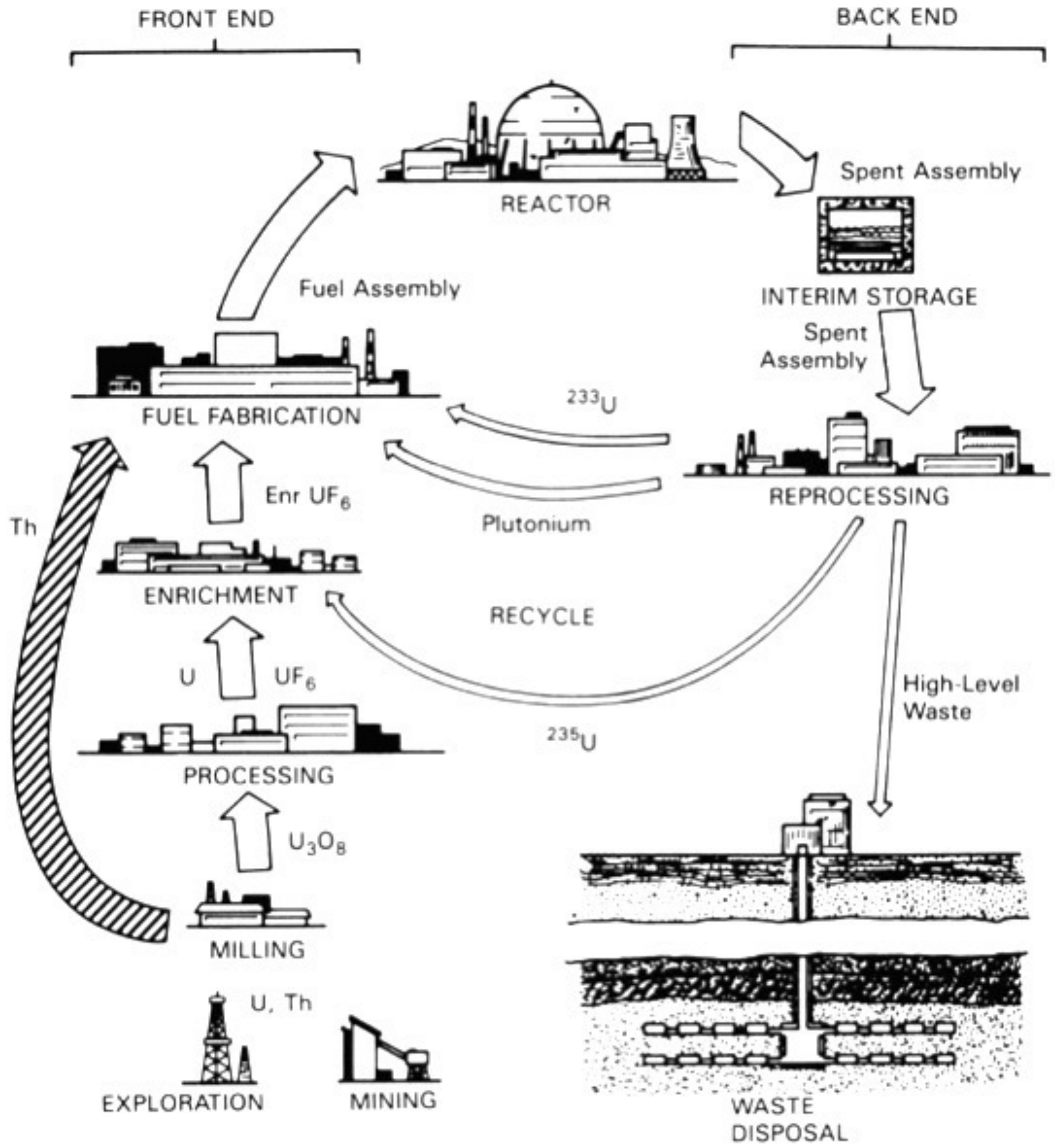
The nuclear fuel cycle



(*Source:* Knief, 2008)

The nuclear fuel cycle (front end)

Mining:

- undergound
- open pit
- in-situ leaching

Ores 0.2% - 12% U

Milling:

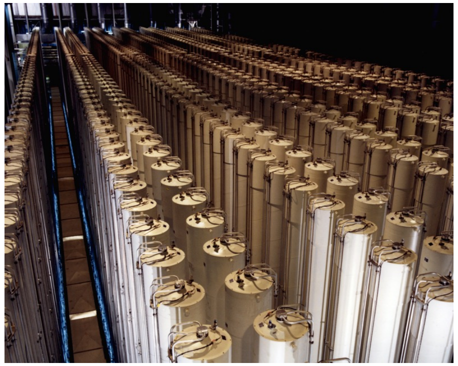
ore processed to make 'yellow cake' (U_3O_8)

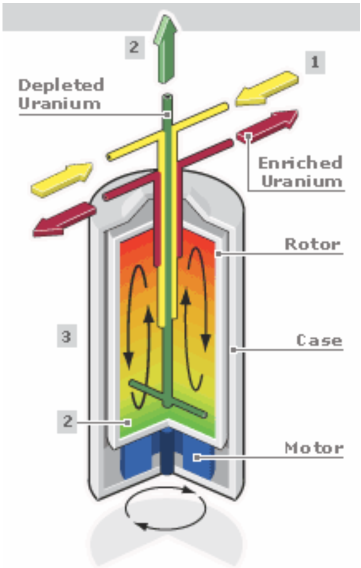
chemical effluents and natural radioactivity in ore residues (tailings)

Conversion:

- enrichment of ^{235}U required
- gaseous form
- yellow cake converted to UF_6

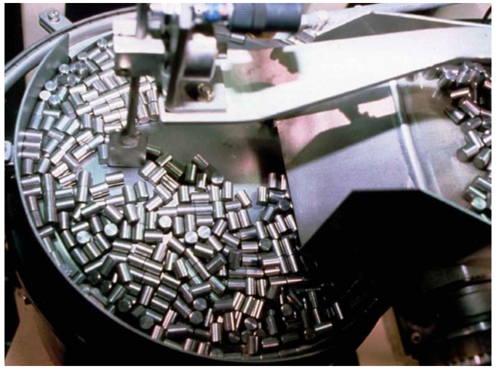
The nuclear fuel cycle (front end - continued)

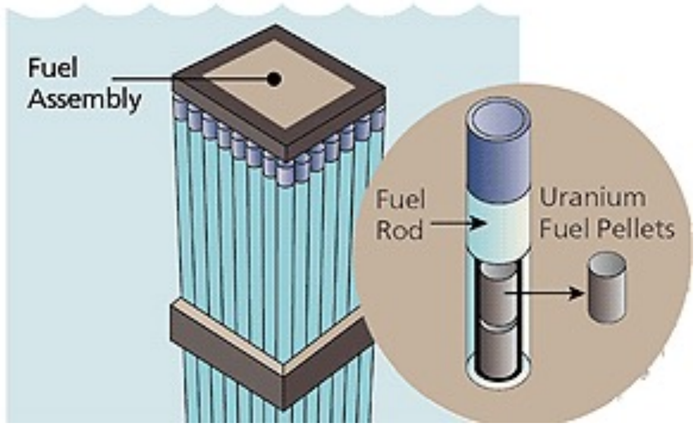




Enrichment:

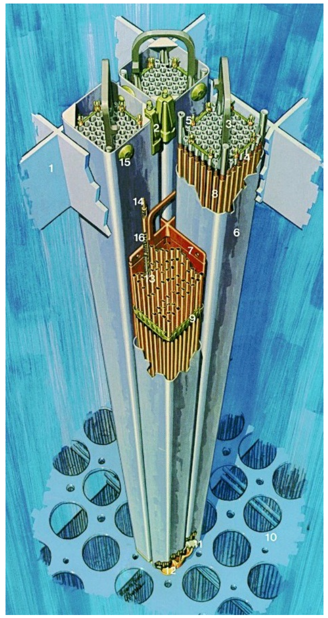
- uranium enriched in ^{235}U by fast spinning centrifugation



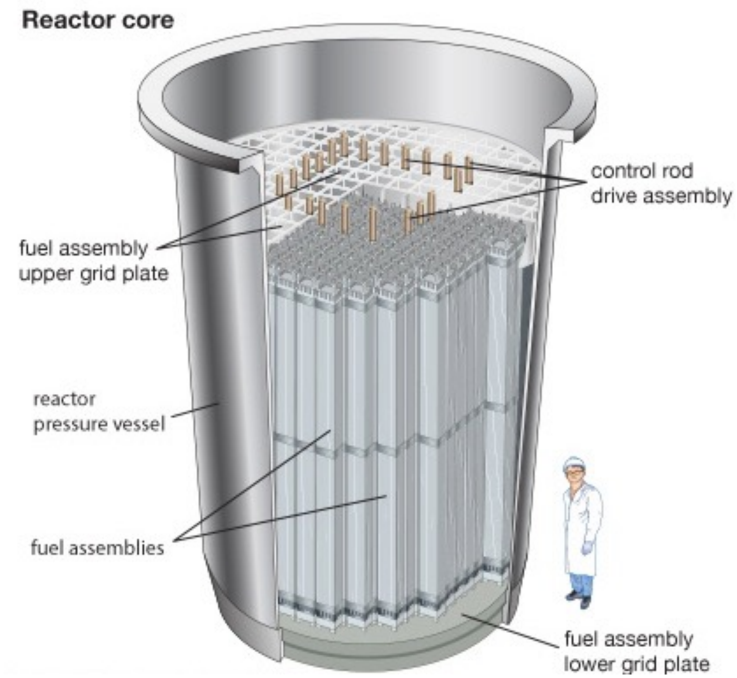


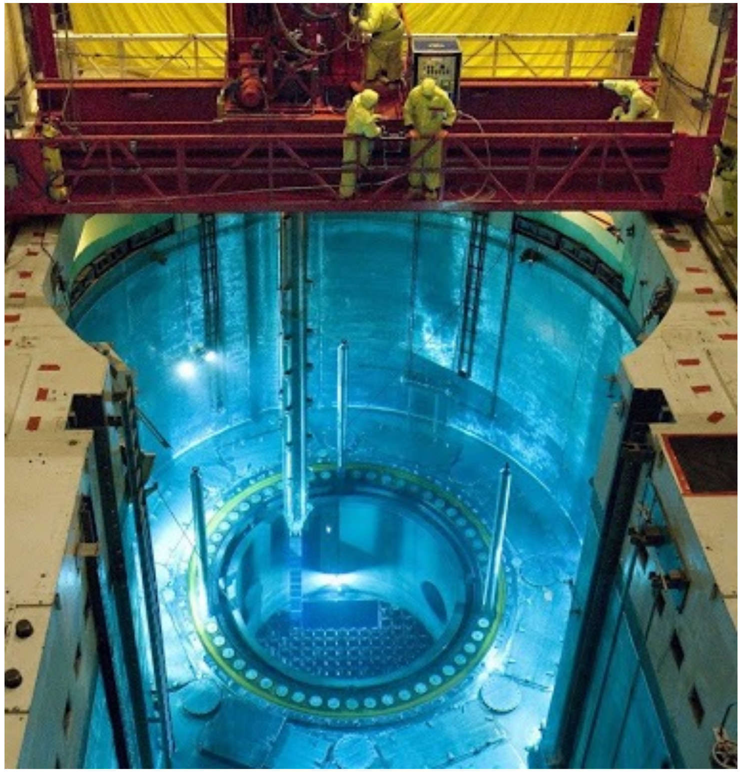
Fuel fabrication:

- UF_6 converted to UO_2
- pellets are 8-15 mm Ø and 10-15 mm long
- packed into fuel rods
- rods (15 × 15) arranged to make up fuel assemblies



Reactor Use





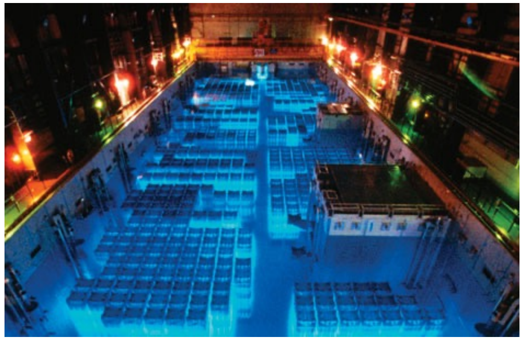
Nuclear reactions:

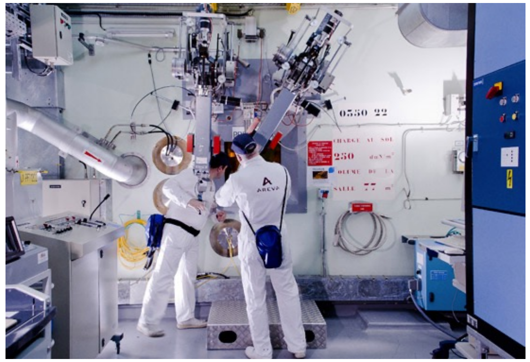
- consume ^{235}U
- produce fissile ^{239}Pu
- generate fission fragments, which 'poison' the chain reaction

Refuelling:

- 1/4 to 1/3 of assemblies replaced each year
- shuffled to maximise amount of energy from each during its 3 – 4 years in the reactor

The nuclear fuel cycle (back end)





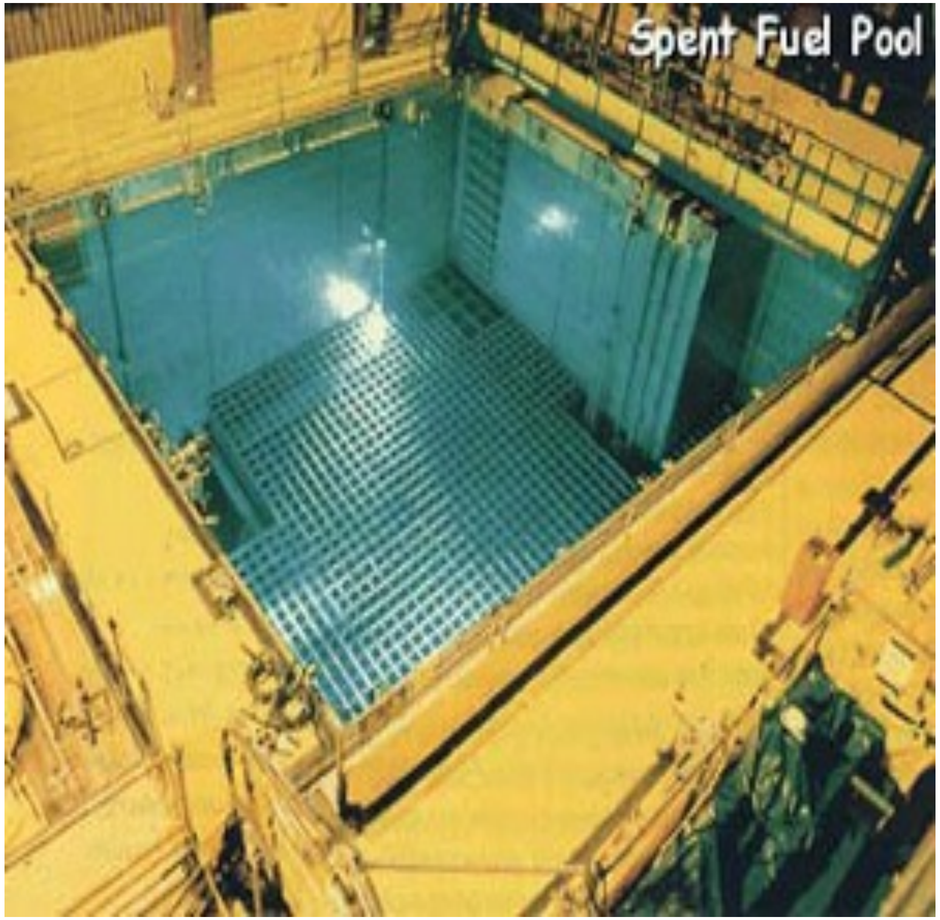
Storage:

- spent fuel assemblies stored under water
- after a few years, fuel can be transferred to interim storage facility (wet or dry storage)
- After 40 yr, radioactivity of fuel is ~1,000 times lower that when removed from reactor

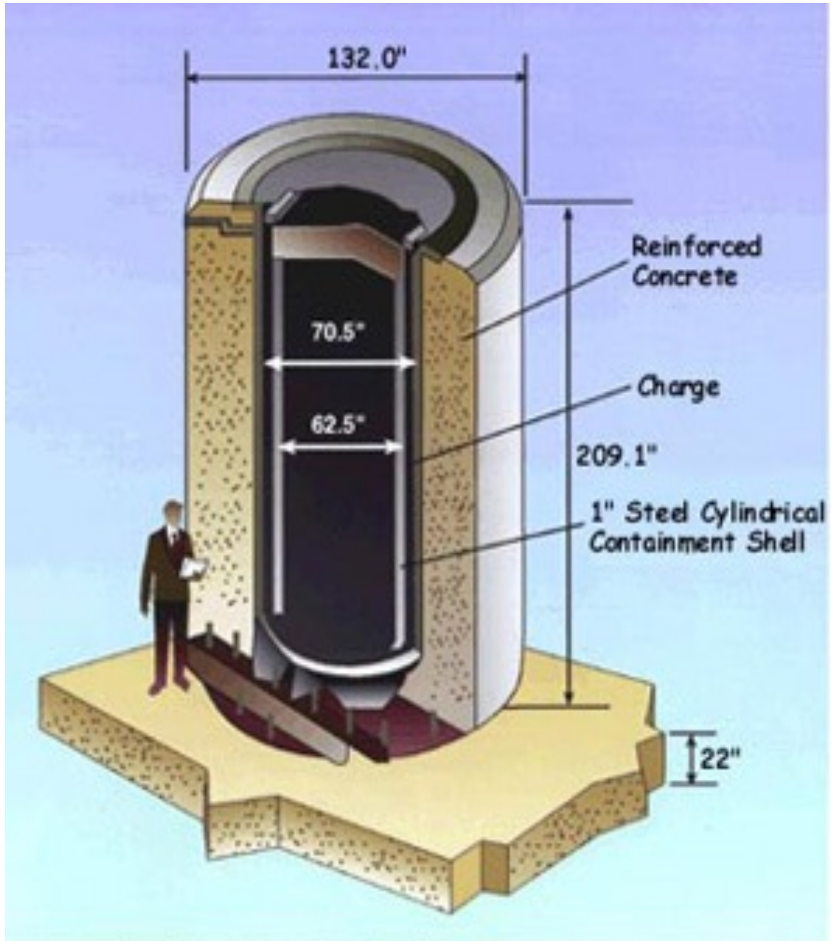
Reprocessing:

- spent fuel contains U (96%), Pu (1%) and HLW (3%)
- U (with less than 1% ^{235}U) can be reused and fed to conversion plant
- Pu can be used to fabricate MOX fuel
- HLW conditioned and packaged for disposal

Spent fuel storage:

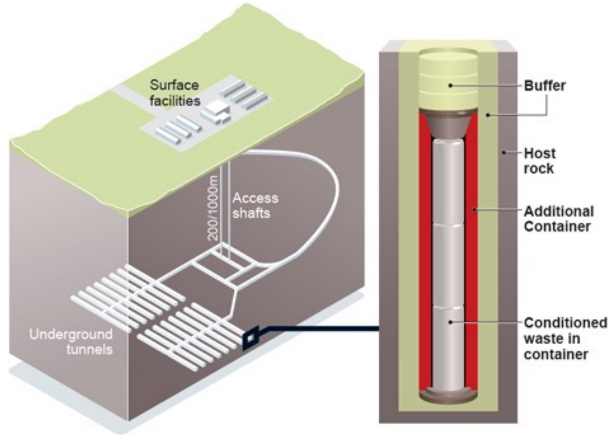


Spent fuel water pond



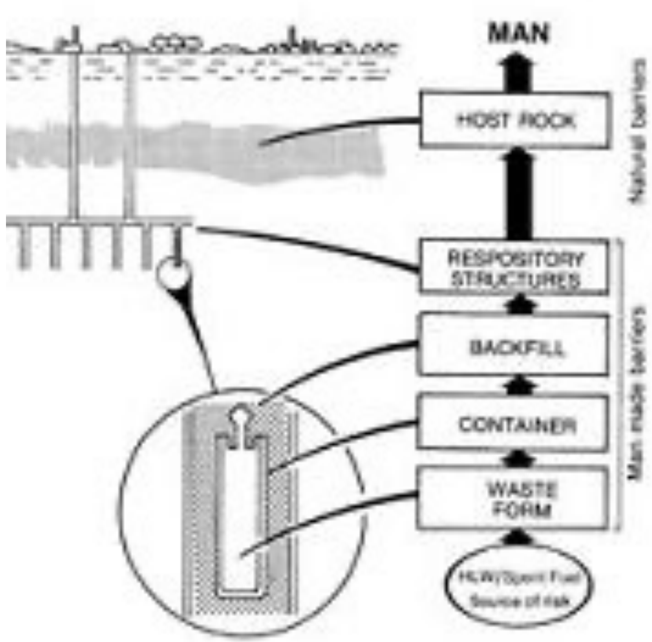
Spent fuel storage cask

The nuclear fuel cycle (back end - continued)

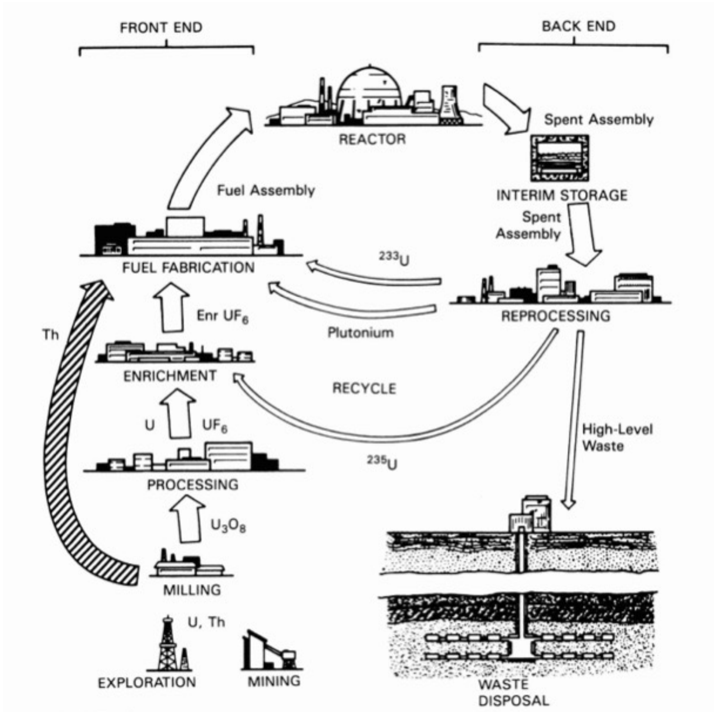


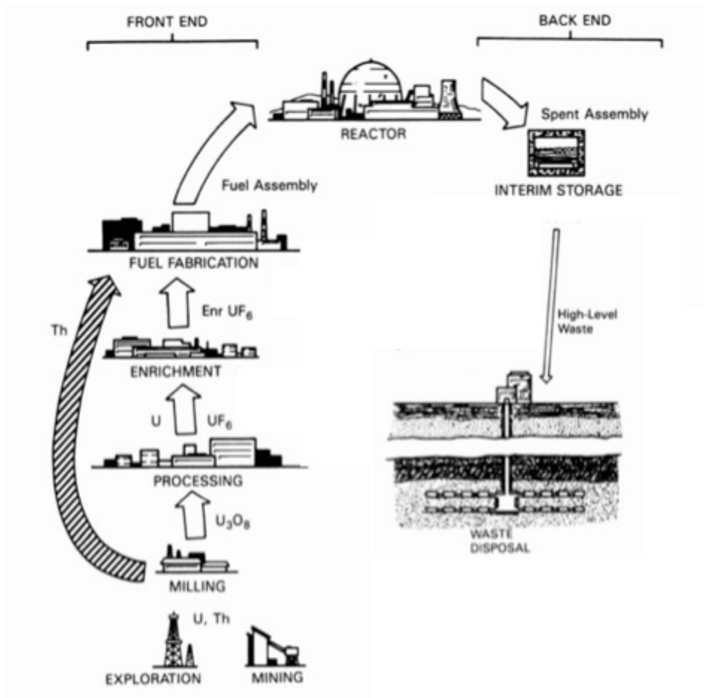
Disposal:

- spent fuel or HLW can be disposed of deep underground
- stable rock formation to minimise risk to people and environment
- Waste packed in long-lasting containers and buried deep underground at locations chosen for geological and geochemistry stability (millions of years)



The closed and open fuel cycles





Closed:

- includes reprocessing of fuel (U and Pu recycled)
- reduction of U requirement by up to 25%
- smaller volume of HL waste

But...

- potential diversion of separated fissile material and high cost

Open:

- fuel only used once before disposal
- lower risk of proliferation

But...

- larger HL waste volume
- waste of useful resource

Some basic nuclear terminology (reminder):

Nuclei are made up of **protons** and **neutrons**, collectively called **nucleons**. A nuclear species is characterised by the total amount of positive charge and by its total mass.

Atomic Number (Z)

Number of protons in a nucleus.

Neutron Number (N)

Number of neutrons in a nucleus.

Mass Number (A)

The total number of protons and neutrons in the nucleus:

$$A = Z + N$$

A species of atom, characterised by its nuclear constitution (*A* and *Z*), is called a **nuclide**.

A given nuclide is conventionally represented by the following symbolic notation:

$$^{A}_{Z}\mathrm{X}$$

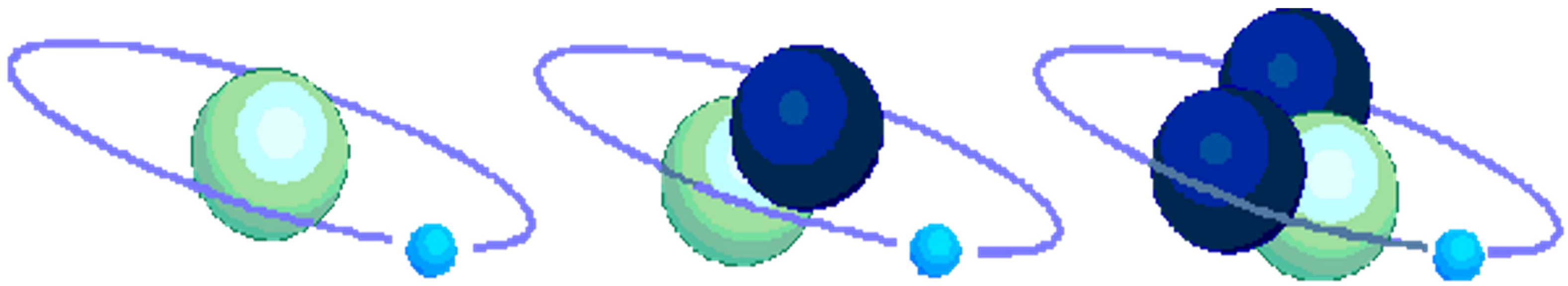
where X is the chemical symbol for the particular element.

$^{1}_{1}\mathrm{H}$, $^{4}_{2}\mathrm{He}$ and $^{238}_{92}\mathrm{U}$ are examples of nuclides.

Each element has a characteristic atomic number (*Z*), but can have several mass numbers (*A*) depending on the number of neutrons (*N*) in the nucleus.

Isotopes are atoms of the same element that have a different number of neutrons

Isotopes cannot be distinguished chemically since they have the same electronic structure and therefore undergo the same chemical reactions. Their nuclear properties, however, can be quite different…



Hydrogen (^{1}H)
Stable

Deuterium (^{2}H)
Stable

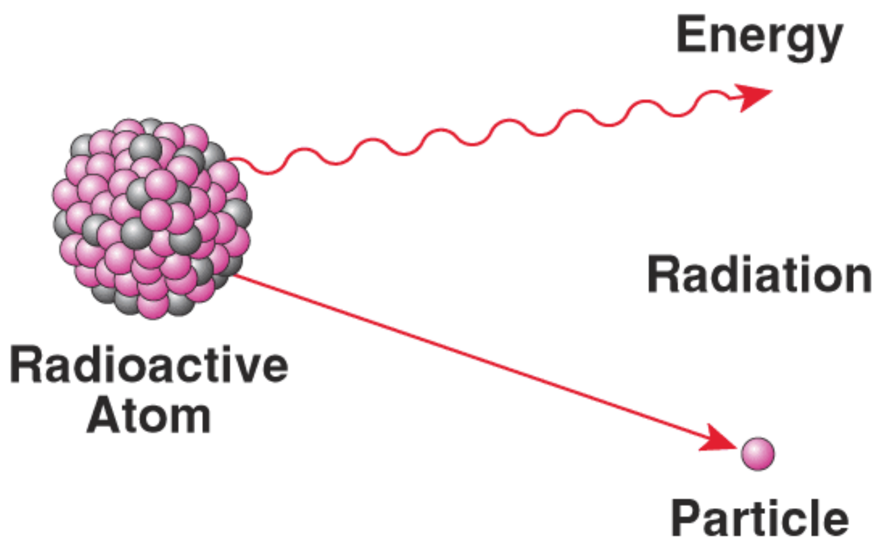
Tritium (^{3}H)
Unstable and radioactive

A radioactive isotope is usually called a radioisotope.

Examples include ^{3}H, ^{60}Co, ^{137}Cs, ^{131}I, ^{238}U, ^{241}Am.

Nuclear stability

There are approximately 260 stable nuclides; hundreds of other nuclides have been observed, but these are unstable and eventually undergo **radioactive decay** by the emission of different types of radiation, spontaneously transforming themselves in the process into a different nuclide.

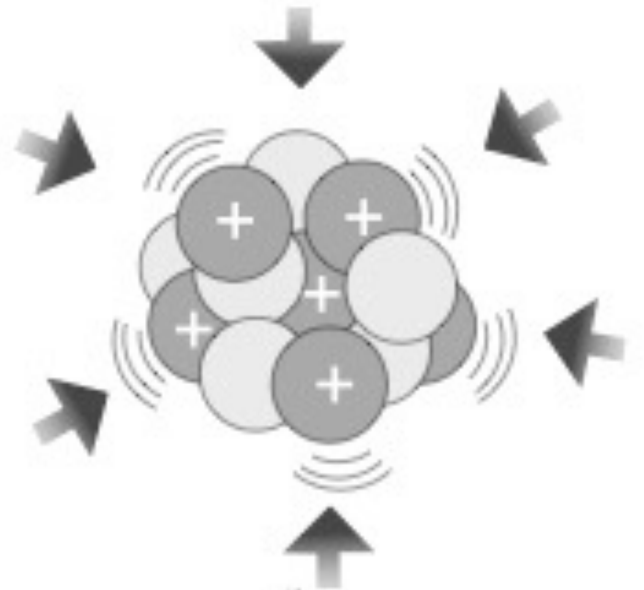


The strong nuclear force and Coulomb repulsion

To keep the protons and neutrons making up the nucleus together, there is a powerful attractive nuclear force, strong enough to overcome the electrostatic repulsion between the protons and to bind the neutrons and protons together into the tiny nuclear volume.

The nuclear force is independent of charge, but is extremely short-ranged – about 3×10^{-15} m.

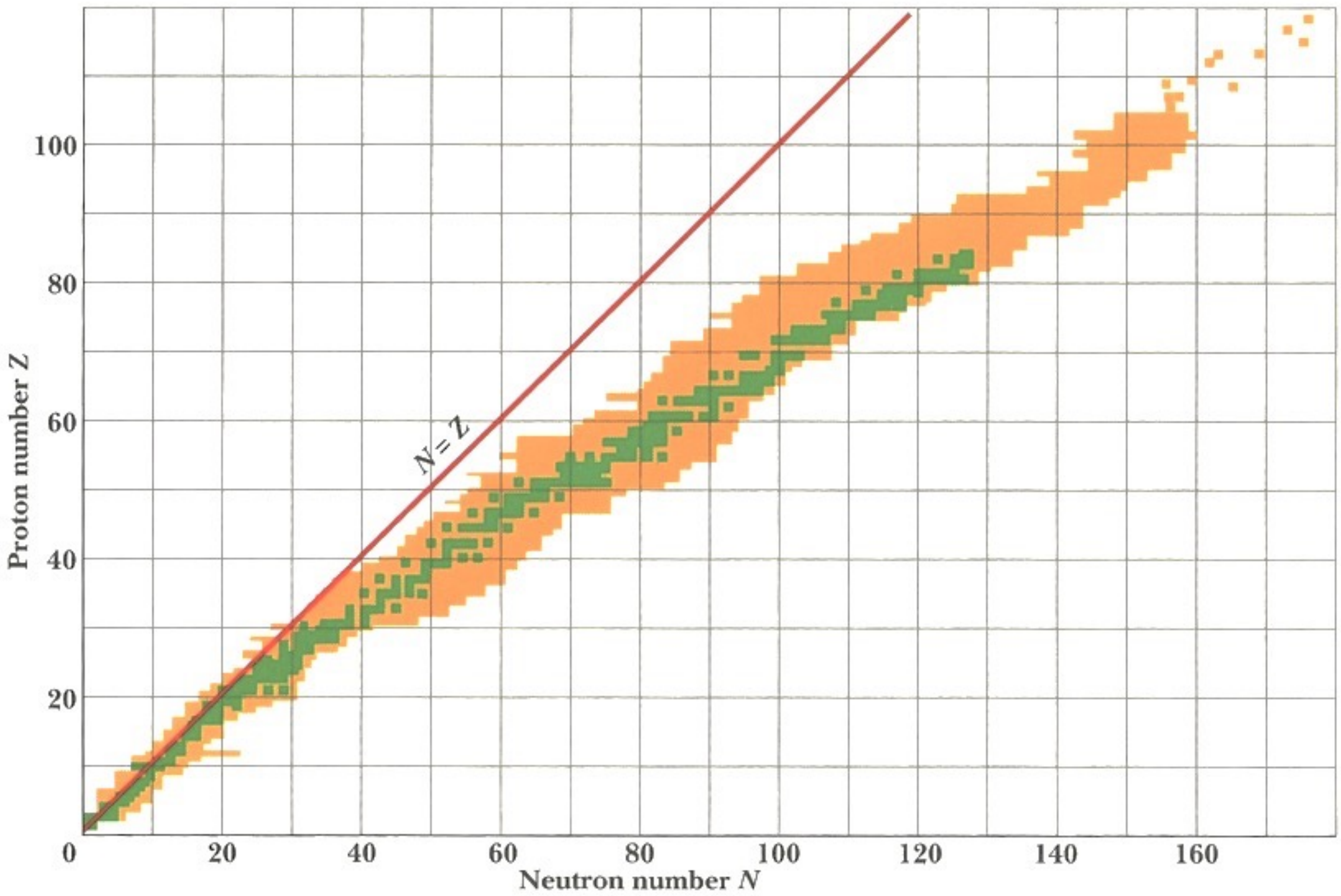
The stability of the nucleus is determined by the balance of the electrostatic and strong nuclear forces.



The exact mode of radioactive transformation depends on the particular type of nuclear instability – i.e., whether the neutron-to-proton ratio in the nuclide is too high or too low – and on the mass-energy relationship among the parent nucleus, daughter nucleus and emitted particle(s).

The relation between the stability of nuclides and their nuclear composition can be visualised on a **nuclide stability diagram** (Segrè chart), in which a nuclide is represented by plotting its neutron number (*N*) against its proton number (*Z*).

Different colours are used to distinguish between stable and unstable nuclides, and between the different modes of radioactive decay.



Nuclide stability diagram. The green shading identifies the band of stable nuclides; the orange shading identifies unstable nuclides

Nuclear energies

Conveniently measured in MeV.

1 MeV = 1.60218×10^{-13} J

Nuclear masses

Masses given in atomic mass units (u): m(^{12}C) = 12.00000 u.

$$1 \text{ u} = 1.6605 \times 10^{-27} \text{ kg}$$

In this system, both p and n have masses of approx. 1 u.

Mass and energy can be interconverted, and so it is common to express masses in energy equivalent or vice versa making use of Einstein's relation $E = m\,c^2$.

1u ➔ 931.49 MeV   and so can use 931.49 MeV/u as conversion factor

Binding energy of the nucleus

The mass of a nucleus is always found to be less than the sum of the masses of its individual protons and neutrons.

To a very good approximation, the difference between the mass of the constituent nucleons and the actual mass of the nucleus can be computed using the following expression:

$$\delta = Z\, m_H + (A - Z)\, m_n - m(^{A}X)$$

where

m_H is the atomic mass of a hydrogen atom (1.0078250 u)

m_n is the mass of the neutron (1.0086649 u)

$m(^{A}X)$ is the **atomic** mass of the nuclide in question

As an example, for ^{17}O (Z = 8; N = 9; A = 17), whose atomic mass is 16.9991317 u:

$$\delta = Z\,m_H + (A - Z)\,m_n - m(^{A}X) =$$

$$= 8\,(1.0078250) + 9\,(1.0086649) - 16.9991317 \text{ u}$$

$$= 0.1414524 \text{ u}$$

The energy equivalent of the mass defect is known as the nuclear binding energy (E_b), and is a measure of the cohesiveness of a nucleus.

E_b can be thought as the energy required to separate the ^{17}O nucleus into its constituent protons and neutrons.

For ^{17}O, $E_b = (0.1414524 \text{ u})\,(931.5 \text{ MeV/u})$

$$\approx 131.76 \text{ MeV}$$

Since the total binding energy of a nucleus depends on the number of nucleons within the nucleus, a more useful measure of the cohesiveness is the average binding energy per nucleon (BE):

$$\mathrm{BE} = \frac{E_\mathrm{b}}{A}$$

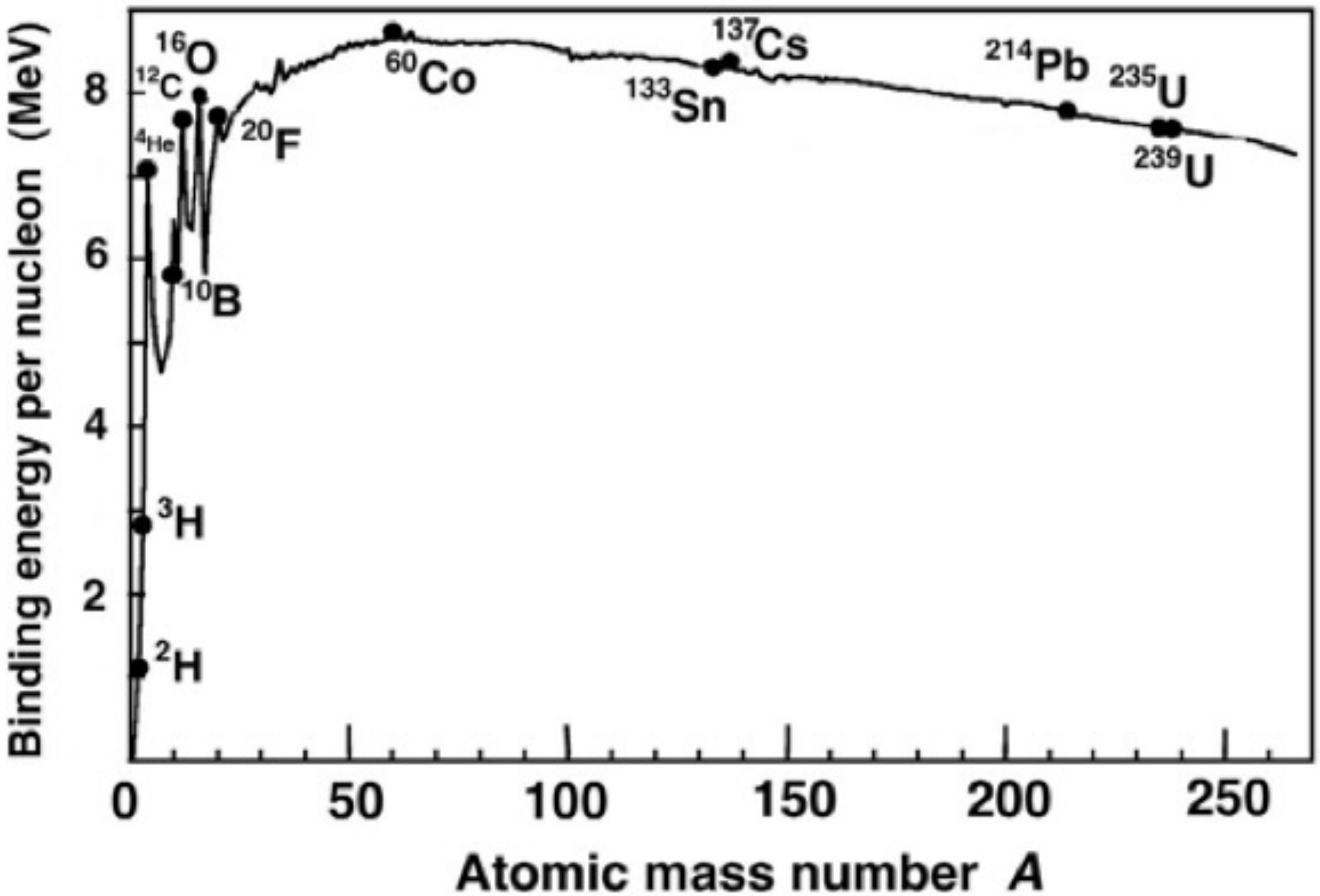
For the case of ^{17}O

$$\mathrm{BE} = \frac{131.76\ \mathrm{MeV}}{17\ \mathrm{nucleons}}$$

$$\approx 7.75\ \mathrm{MeV/nucleon}$$

A plot of BE versus *A* shows a broad maximum in excess of 8 MeV/nucleon between mass numbers 50–100.

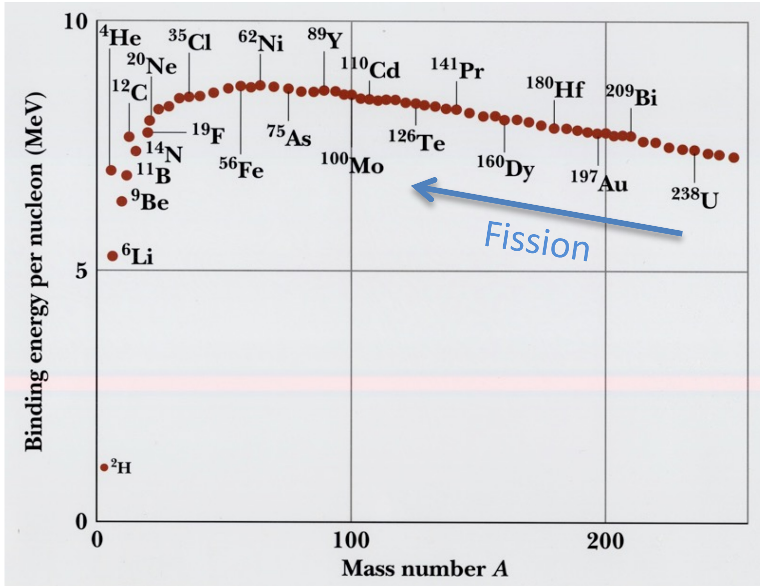
At lower and higher mass numbers, BE is less.

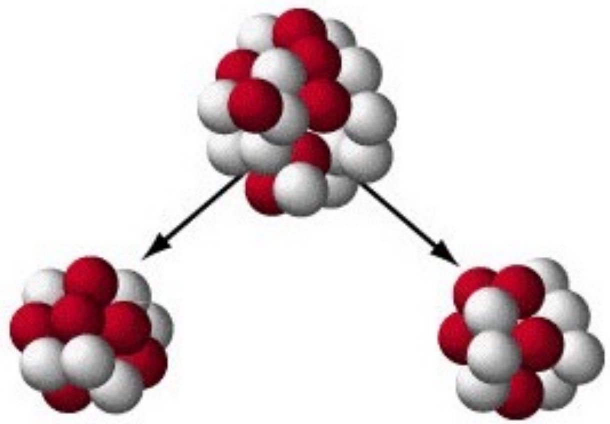


The drooping of the binding energy curve at both high and low mass numbers is of the most profound importance.

Because nuclei of middle mass are more tightly bound (higher BE) than heavy ones, energy will be released by moving down the nuclear binding energy curve.

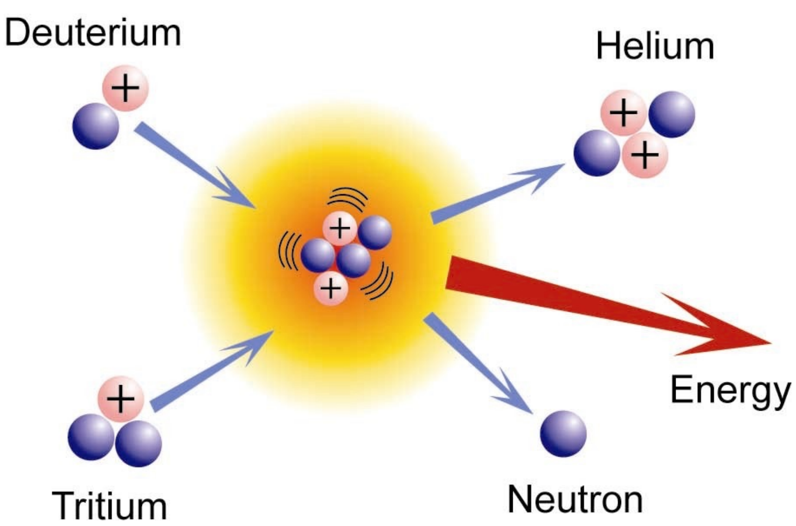
In other words, energy can be released by the splitting, or nuclear fission, of a single massive nucleus into two smaller fragments.

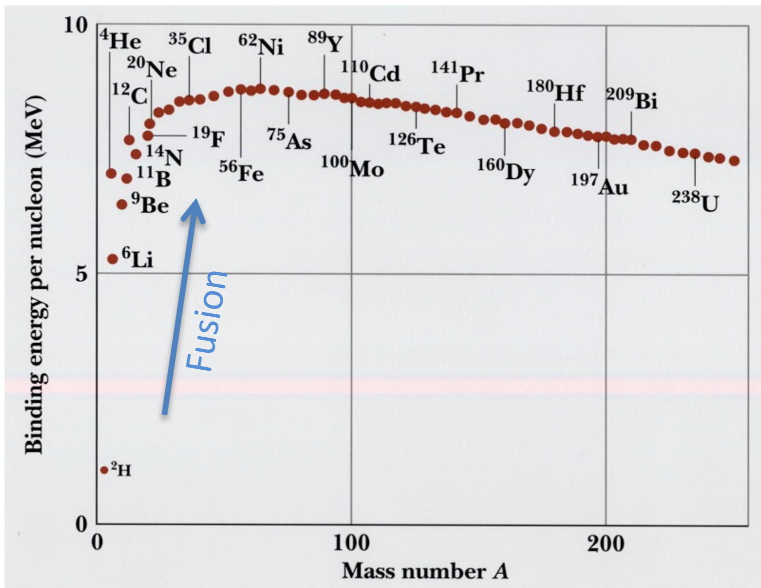




Similarly, energy is released when light isotopes combine to form a heavier nucleus with higher average binding energies per nucleon (moving up the nuclear binding energy curve) .

This process is called nuclear fusion, and is the source of energy that drives our Sun and other stars, as well as thermonuclear explosions (i.e., the 'hydrogen' bomb).





Energy released in fission

Consider the following process:

$$^{238}_{92}\mathrm{U} \quad \rightarrow \quad ^{119}_{46}\mathrm{Pd} + {}^{119}_{46}\mathrm{Pd}$$

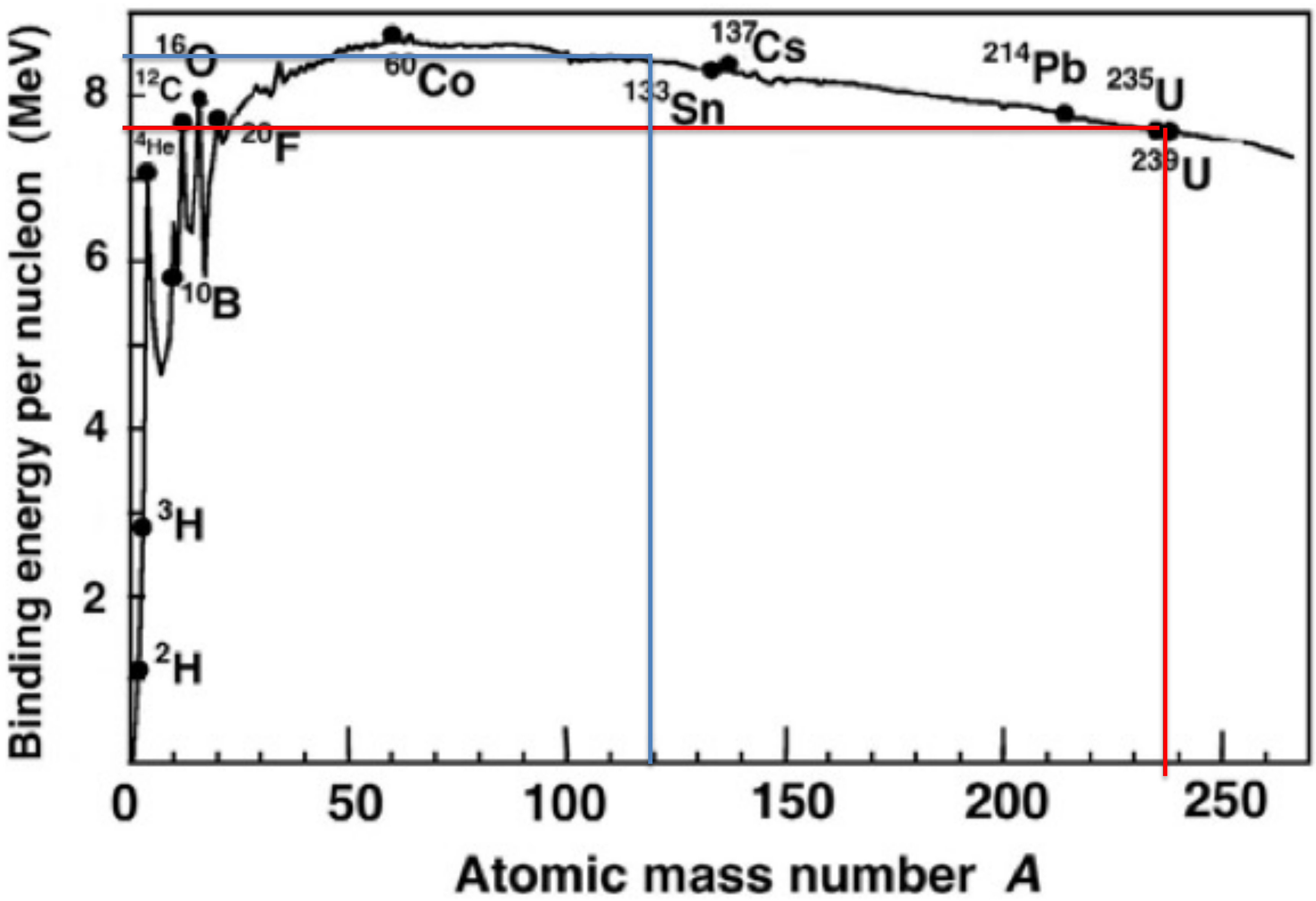
Energy balance: bound ^{238}U = 238 × 7.6 = 1809 MeV

two bound ^{119}Pd = 2 × 119 × 8.5

= 2023 MeV

More tightly bound system means the energy difference (i.e., 2023 – 1809 = 214 MeV) must be released.

This energy would appear as kinetic energy of the two fragments (this energy can be captured to produce heat that can be used for electricity generation).



Binding energy per nucleon (MeV)
8
6
4
2
0
50
100
150
200
250
Atomic mass number A
16O
12C
4He
3H
2H
10B
20F
60Co
133Sn
137Cs
214Pb
235U
239U

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Fission – why do we bother?

Compare energy released in fission to that from burning coal

Coal burning: $$C + O_2 \rightarrow CO_2$$

$$\Delta E \approx 10^5 \text{ J/g}$$

Nuclear Fission: $${}^{238}_{92}\text{U} \rightarrow {}^{119}_{46}\text{Pd} + {}^{119}_{46}\text{Pd}$$

$$\Delta E \approx \frac{214 \text{ MeV} \times N_A}{238 \text{ g/mole}} \times 1.6\ 10^{-13} \text{ J/MeV}$$

$$\approx 10^{11} \text{ J/g}$$

Nuclear reactions produce ~10^6 more energy per unit mass than do chemical reactions.