Joint ICTP-IAEA-MAMBA School on Materials Irradiation: from Basics to Applications

Management of nuclear waste: Transmutation

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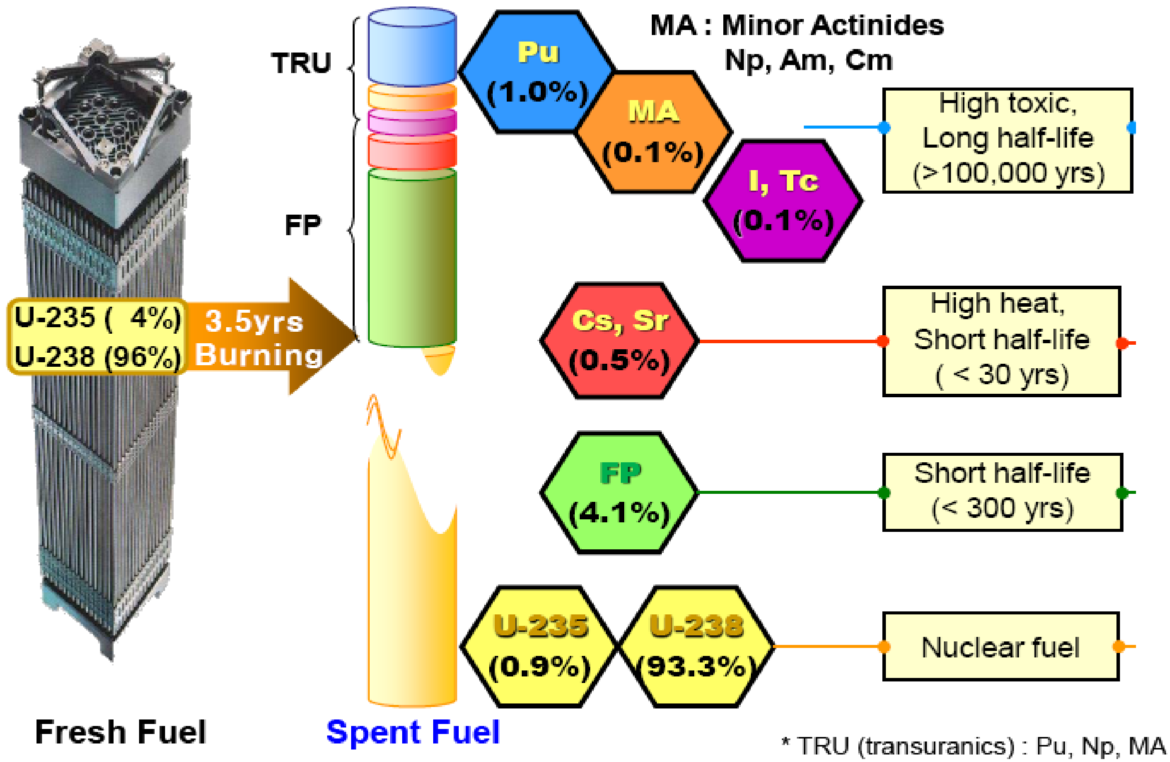
Contents

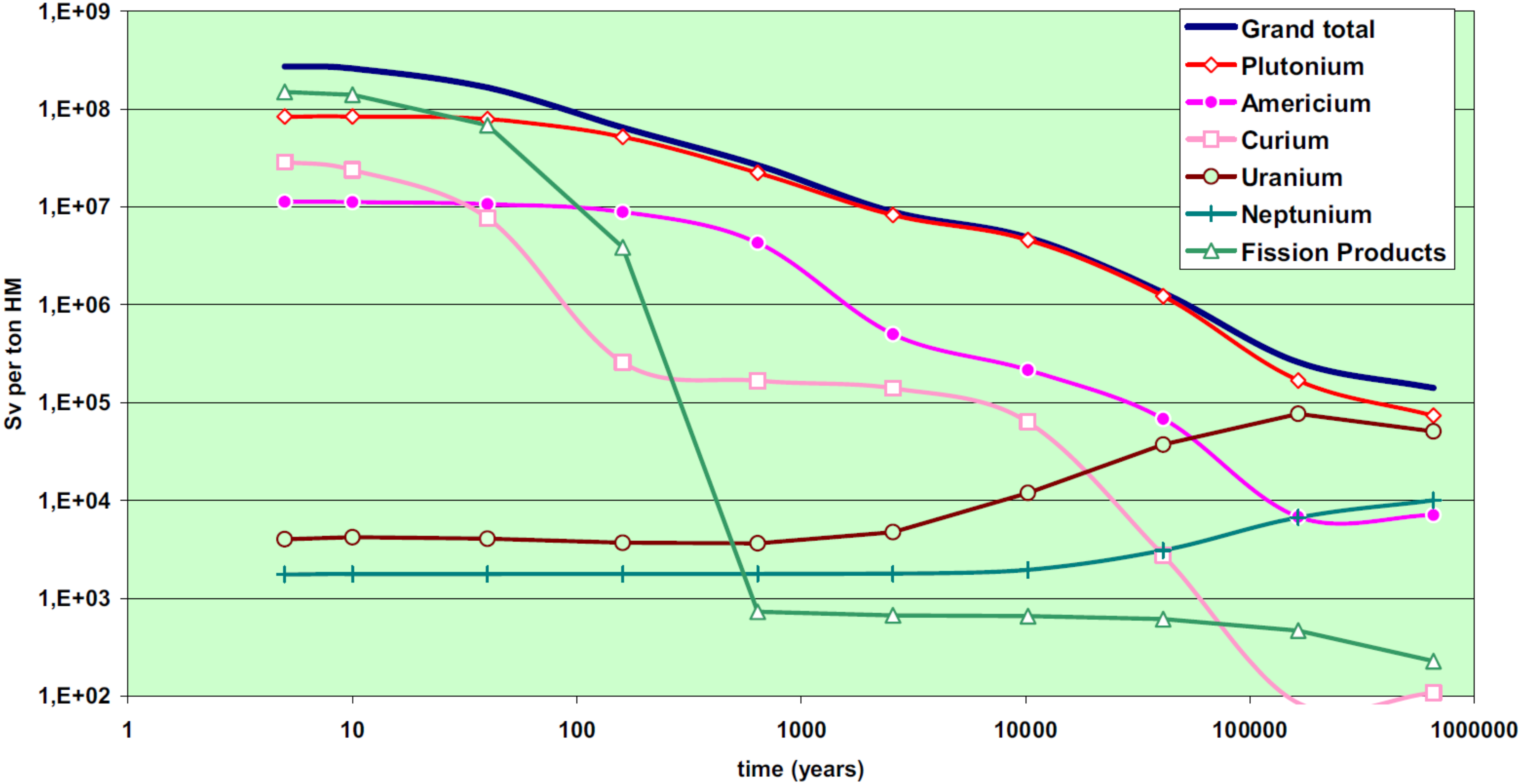
Contents

Components of the spent fuel

- Uranium + activated structural materials: large mass/volume, low radioactivity
- Fission fragments: 5% of waste, large radiation but low life (30 years)
- Transuranic (TRU) elements (Pu, Am, Np, Cm): 1.5% of waste, large contribution to radioactivity, fissionable, life between 20000 and 10000000 yr



Radiotoxicity of the spent fuel



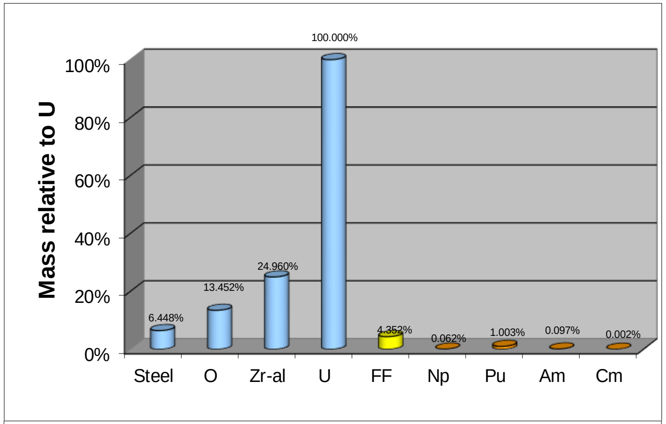
Source: ***RED-IMPACT project***.

Components of the spent fuel

❑ Divide

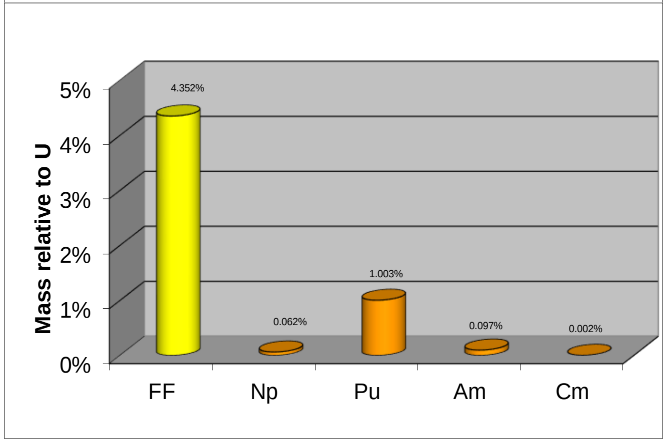
Solution adapted to every type of waste

- ➢ Uranium: reuse or disposal near surface
- ➢ Fission fragments: decay in an interim storage near surface
- ➢ TRUs: Remove by means of conversion to energy or other isotopes with shorter lifetime



❑ Recycle

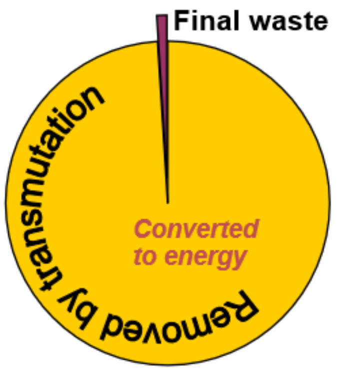
TRUs are fissioned in special systems or in Generation IV fast reactors → energy + fission fragments



❑ Repeat the cycle

Repeating division and recycling leads to the removal of 99% of radioactive isotopes.

Remaining 1% is sent to final disposal (problem is reduced in a factor 100)



Contents

Transmutation

Transmutation transforms Pu and Minor Actinides (Np, Am, Cm?) into fission fragments

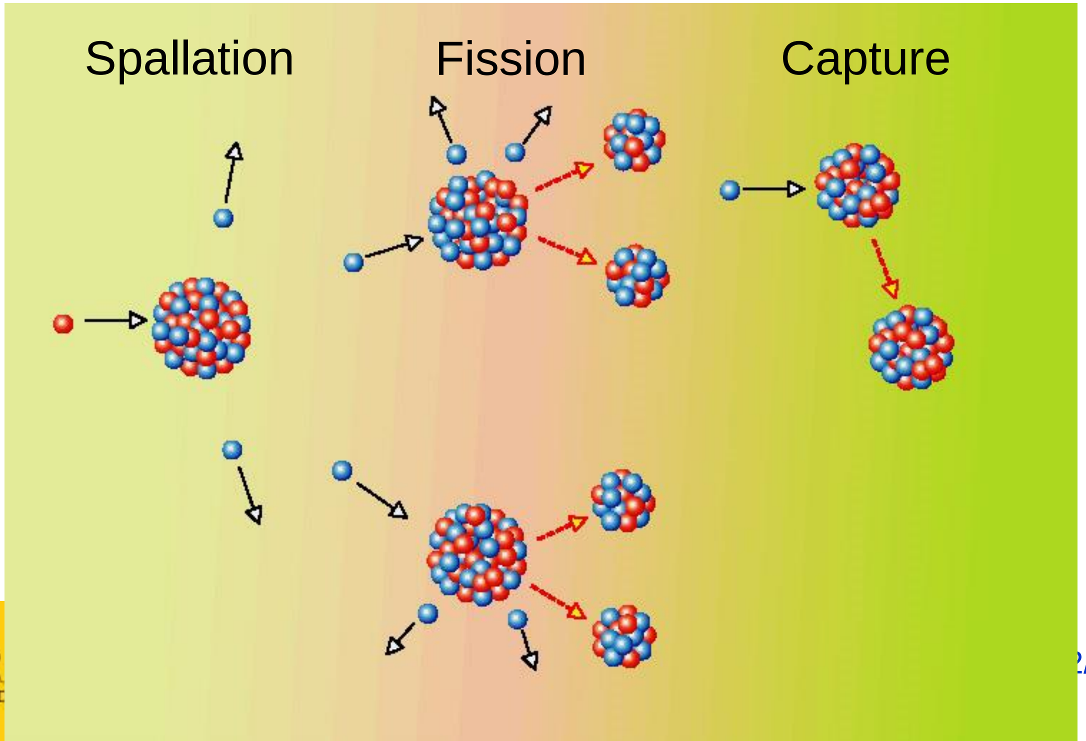
$n + {}^{239}Pu$ (24000 yr) $\rightarrow$ ${}^{134}Cs$ (2 yr)+ ${}^{104}Ru$ (stable) + 2 n + 200 MeV

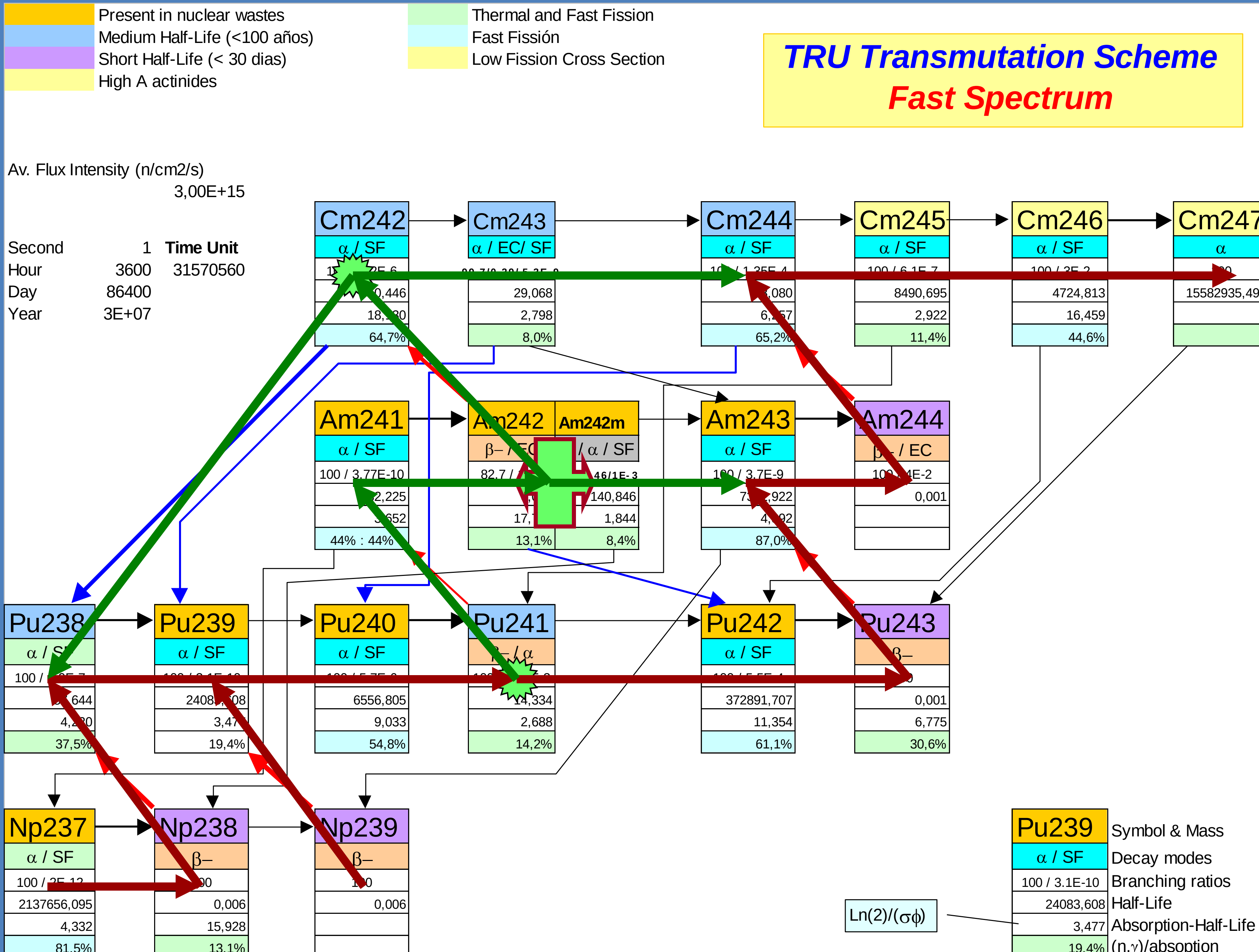
$n + {}^{241}Am$ (432 yr) $\rightarrow$ ${}^{242}Am$ (16 h) [capture]

${}^{242}Am$ (16 h) $\rightarrow$ ${}^{242}Cm$ (163 d) [β- decay]

${}^{242}Cm$ (163 d) $\rightarrow$ ${}^{238}Pu$ (88 yr) [α decay]

$n + {}^{238}Pu$ (88 yr) $\rightarrow$ ${}^{142}Ce$ (stable)+ ${}^{95}Zr$ (64 d) + 2 n + 200 MeV




Present in nuclear wastes
Medium Half-Life (<100 años)
Short Half-Life (< 30 dias)
High A actinides
Thermal and Fast Fission
Fast Fissión
Low Fission Cross Section
TRU Transmutation Scheme
Fast Spectrum
Av. Flux Intensity (n/cm2/s)
3,00E+15
Second 1 Time Unit
Hour 3600 31570560
Day 86400
Year 3E+07
Cm242
α / SF
64,7%
Cm243
α / EC/ SF
29,068
2,798
8,0%
Cm244
α / SF
65,2%
Cm245
α / SF
100 / 6.1E-7
8490,695
2,922
11,4%
Cm246
α / SF
100 / 3E-2
4724,813
16,459
44,6%
Cm247
α
15582935,494
Am241
α / SF
100 / 3.77E-10
44% : 44%
Am242
Am242m
13,1%
140,846
1,844
8,4%
Am243
α / SF
100 / 3,7E-9
87,0%
Am244
β– / EC
0,001
Pu238
37,5%
Pu239
α / SF
19,4%
Pu240
α / SF
6556,805
9,033
54,8%
Pu241
14,334
2,688
14,2%
Pu242
α / SF
372891,707
11,354
61,1%
Pu243
β–
0,001
6,775
30,6%
Np237
α / SF
2137656,095
4,332
81,5%
Np238
β–
0,006
15,928
13,1%
Np239
β–
0,006
Pu239
α / SF
100 / 3.1E-10
24083,608
3,477
19,4%
Symbol & Mass
Decay modes
Branching ratios
Half-Life
Absorption-Half-Life
(n,γ)/absoption
Ln(2)/(σφ)

Transmutation

Transmutation transforms Pu and Minor Actinides (Np, Am, Cm?) into fission fragments

n + ^{239}Pu (24000 yr) $\rightarrow$ ^{134}Cs (2 yr)+ ^{104}Ru (stable) + 2 n + 200 MeV

n + ^{241}Am (432 yr) $\rightarrow$ ^{242}Am (16 h) [capture]

^{242}Am (16 h) $\rightarrow$ ^{242}Cm (163 d) [β- decay]

^{242}Cm (163 d) $\rightarrow$ ^{238}Pu (88 yr) [α decay]

n + ^{238}Pu (88 yr) $\rightarrow$ ^{142}Ce (stable)+ ^{95}Zr (64 d) + 2 n + 200 MeV

Optionally: long lived FF are transformed by radioactive capture in stable isotopes

n + ^{99}Tc (210000 yr) $\rightarrow$ ^{100}Tc (16 s) + γ.

^{100}Tc (16 s) $\rightarrow$ ^{100}Ru (stable) [β-]

n + ^{129}I (15.700.000 yr) $\rightarrow$ ^{130}I (12 h) + γ.

^{130}I (12 h) $\rightarrow$ ^{130}Xe (stable) [β-]

Transmutation needs many neutrons and produces a lot of energy!

Considerations about transmutation

1) Large neutron flux and capacity of extracting energy is needed.

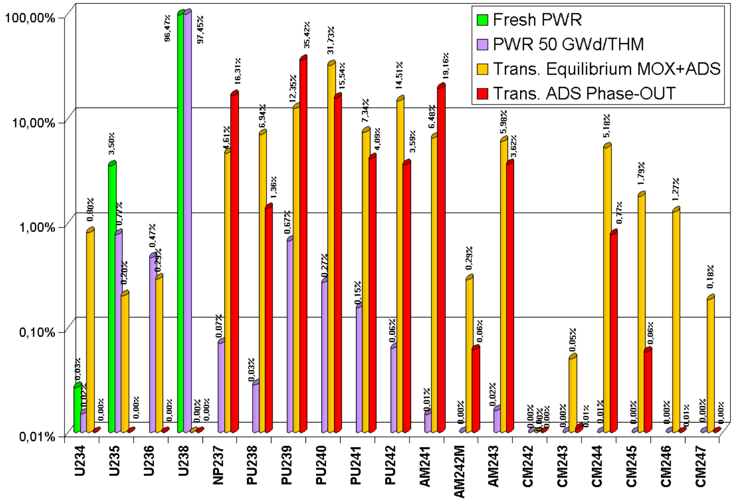
2) Each TRU transmutation involves a fission reaction. The time needed to produce the transmutation of a certain amount of waste is inversely proportional to the fission rates= Installed thermal power.

3) To increase the transmutation probability the fuel must contain a large TRU fraction.

4) Pu and MA are produced by captures in U-238 with low energy neutrons. To limit the production of new waste, the transmuter should be a reactor without or with very Little uranium in the fuel.

5) Regarding the neutron spectrum:
   a. It is irrelevant for the transmutation capacity
   b. It conditions the transmuter viability
   c. It defines the isotopic composition of the final waste (fast spectrum desired)

Additionally, we need to separate TRUs from U!



Considerations about transmutation

We need a reactor with a high power (hundreds or thousand MW) with fast spectrum, with low uranium (U-238) content and high content of Pu and MA (TRUs).

This type of systems show intrinsic safety issues when increasing the amount of TRUs:

- Low fraction of delayed neutrons
- Low Doppler effect
- Bad void worth (in particular with Na)

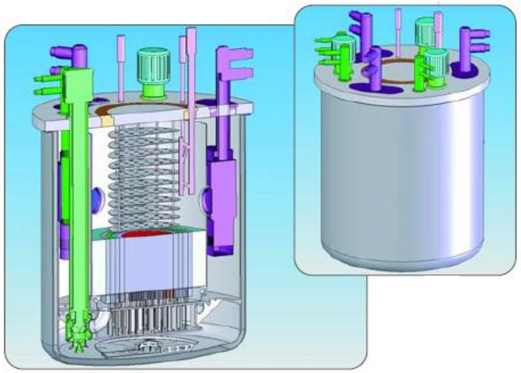
And need a great operation flexibility:

- High level of burn-up
- Strong evolution of fuel reactivity with burn-up

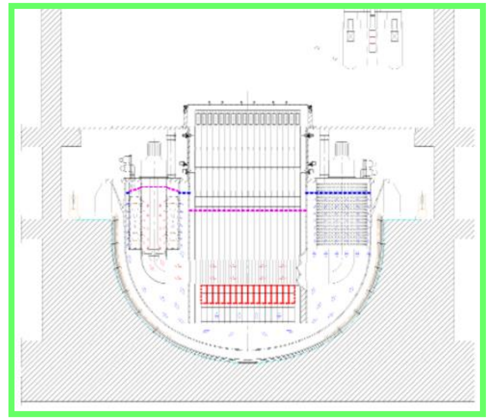
Possible solutions:

- A large number of Generation IV reactors with small amount of TRU in the fuel.
- A large number of Generation IV reactors with small zones devoted to transmutation.
- A small number of dedicated systems (or reactors of MSR type).

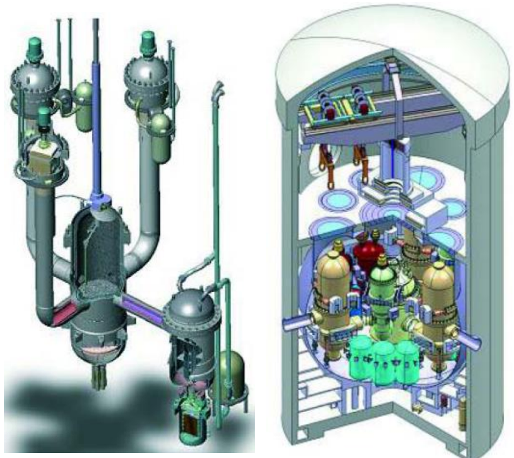
Generation IV fast reactors



Liquid sodium: ASTRID
CP-ESFR, ESFR-SMART



Liquid lead: ALFRED,
EURATOM, ELSY, CDT,
LEADER, HeLiMnet,
MYRRHA



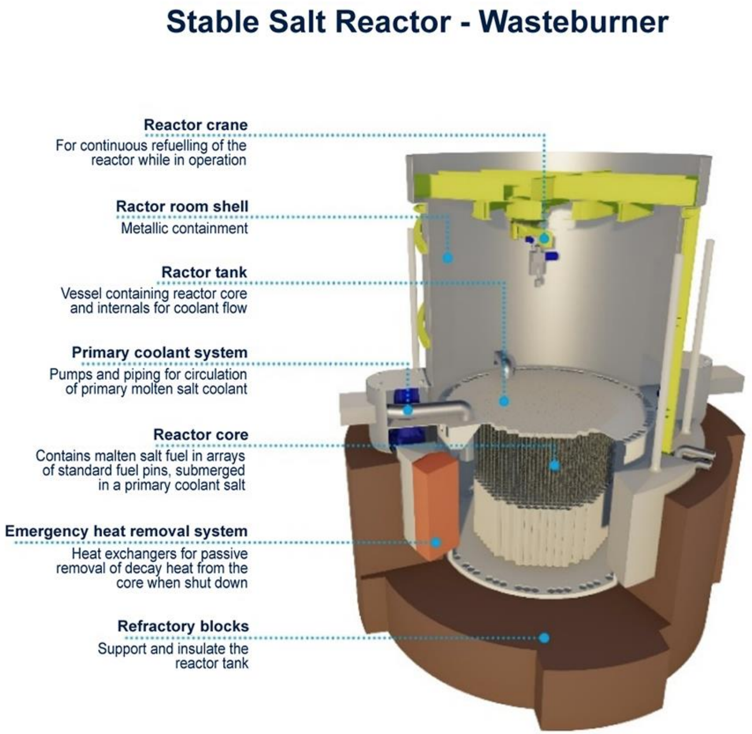
Gas: ALLEGRO,
GoFastR

Materials to be transmuted are incorporated to the fuel or in specific targets.

Gen IV fast reactors:	
Long term sustainability: Fuel availability and waste minimization	**Economics:** Competitive generation and financial costs
Security and Reliability: Excel in safety, low core damage, no external emergency plan	**Resistance to proliferation and physical protection:** Minimization of proliferation attractiveness and protection against terrorist acts

Molten salt reactors

- The molten salt technology (MSR) is usually included as one categoy of small modular reactors (SMR).
- Included in Generación IV International Forum.
- Possible molten fuel mixed with the coolant or separated from the salt.
- Fluorides or chlorides.
- Fast or epithermal neutron spectrum for transmutation.
- Fuels made of Th, U, Pu, MA.

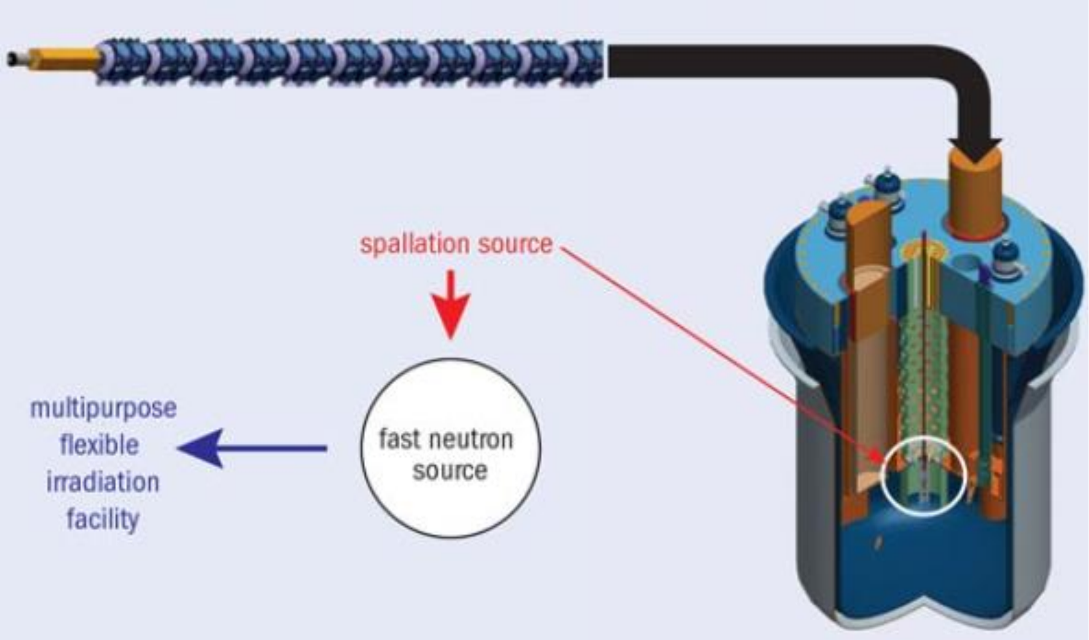


Moltex Energy is developing a molten salt reactor for waste transmutation, together with a facility for spent fuel reprocessing.

Source: *Nuclear España* journal

Accelerator driven subcritical system (ADS)

An ADS is a subcritical nuclear system (k_{eff} = 0.95-0.98) where the power is maintained by an external source of neutrons with large intensity. Usually, they are produced by spallation induced by light particles (protons) with high energy (close to 1 GeV) in heavy nuclides.



Materials to be transmuted are contained in the fuel.

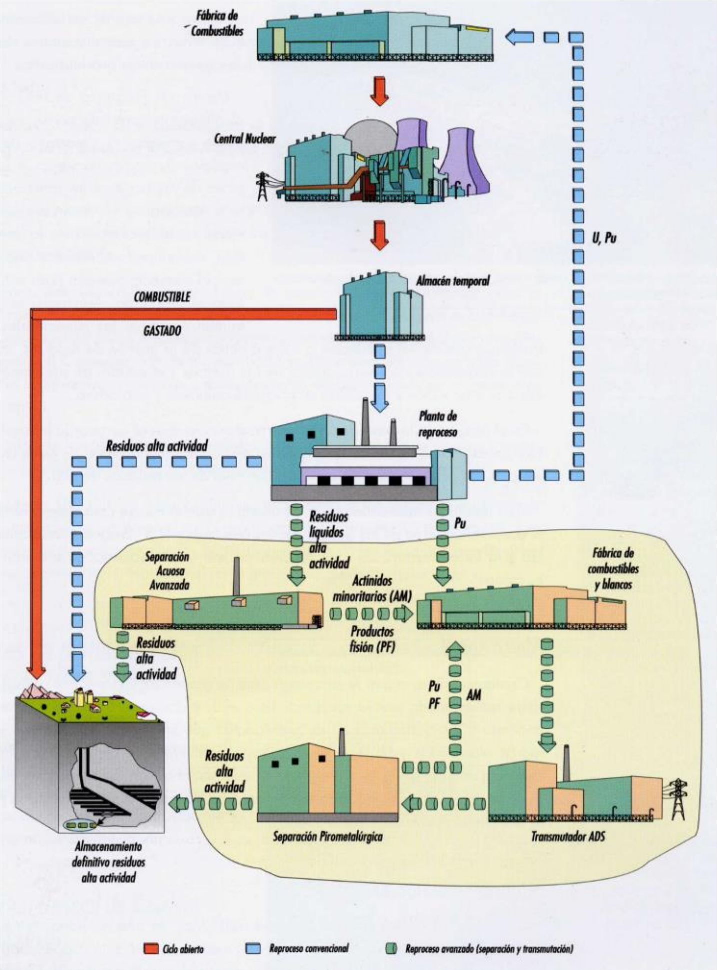
ADS advantage: Designed to accept fuel intrinsically unsafe (in critical mode) and adapted to large changes in reactivity.

Contents

Nuclear fuel cycle

Partitioning (separation) and transmutation (**P&T**) processes introduce new elements in the fuel cycle, before the final disposal of the waste:

- Reprocessing plants for the spent fuels of current reactors
- Fabrication facilities for the fuels and targets of transmuters
- Transmutation systems
- Reprocessing plants for the spent fuels of advanced systems
- Interim storage facilities

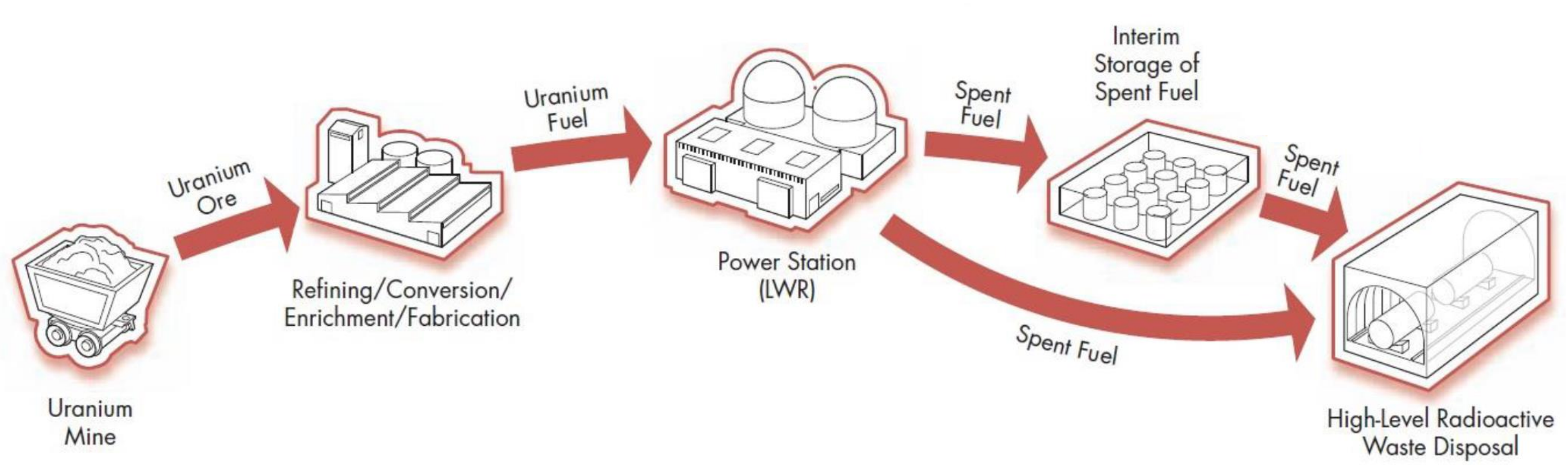


The different combinations of these elements provide different versions of advanced fuel cycles with transmutation.

Elements of the fuel cycle do not have to be localized in a single country.
Collaboration between countries allow optimizing the use of the facilities.

Nuclear fuel cycle

Open cycle (once-through)

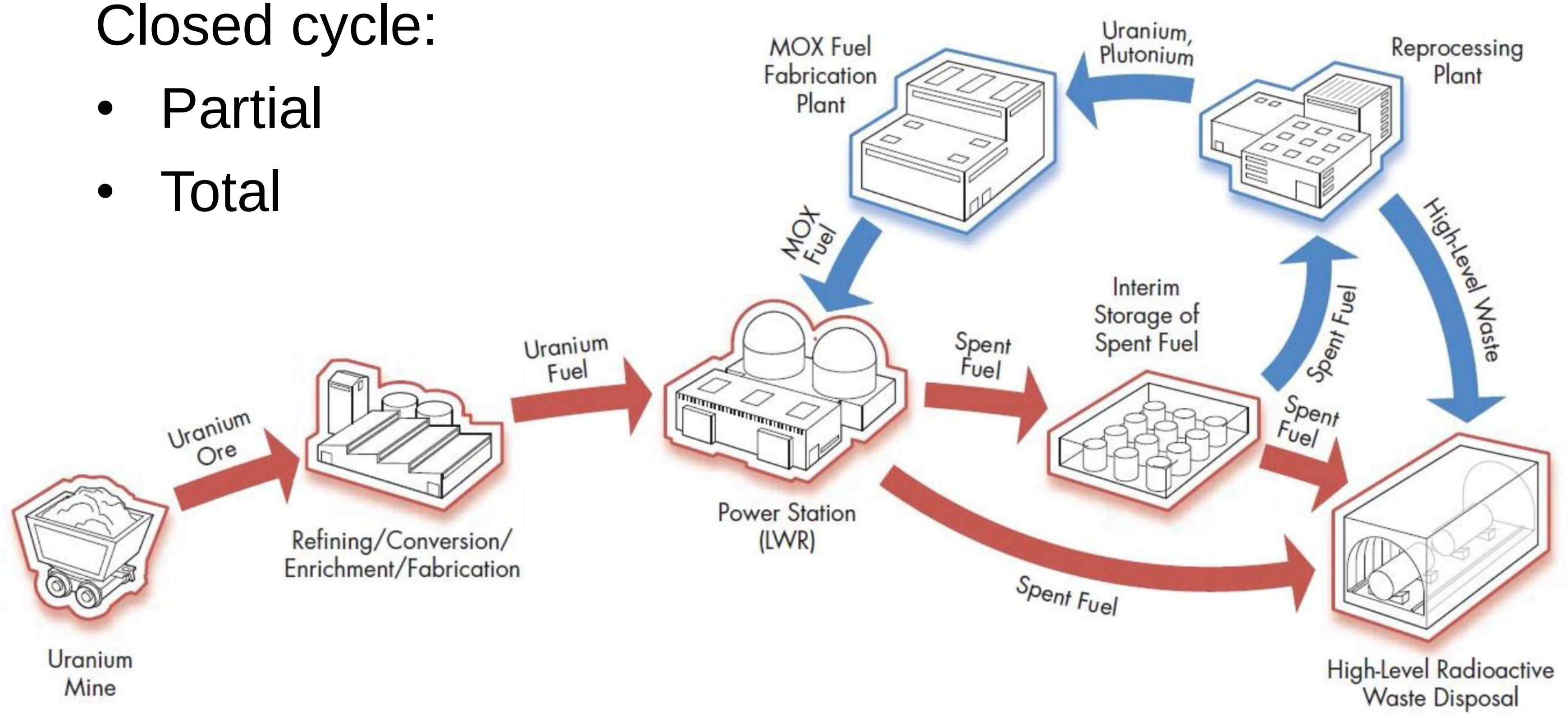


Source: A. Clamp. Toward an Integrated Nuclear Fuel Cycle. EPRI Journal, 2008 Spring

Nuclear fuel cycle

Closed cycle:

- Partial
- Total



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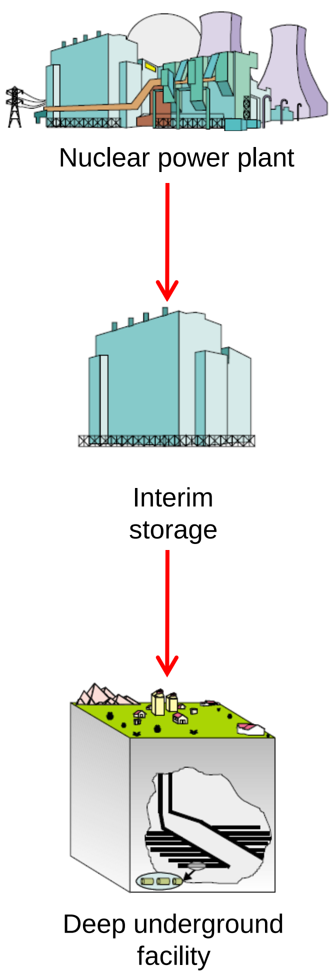
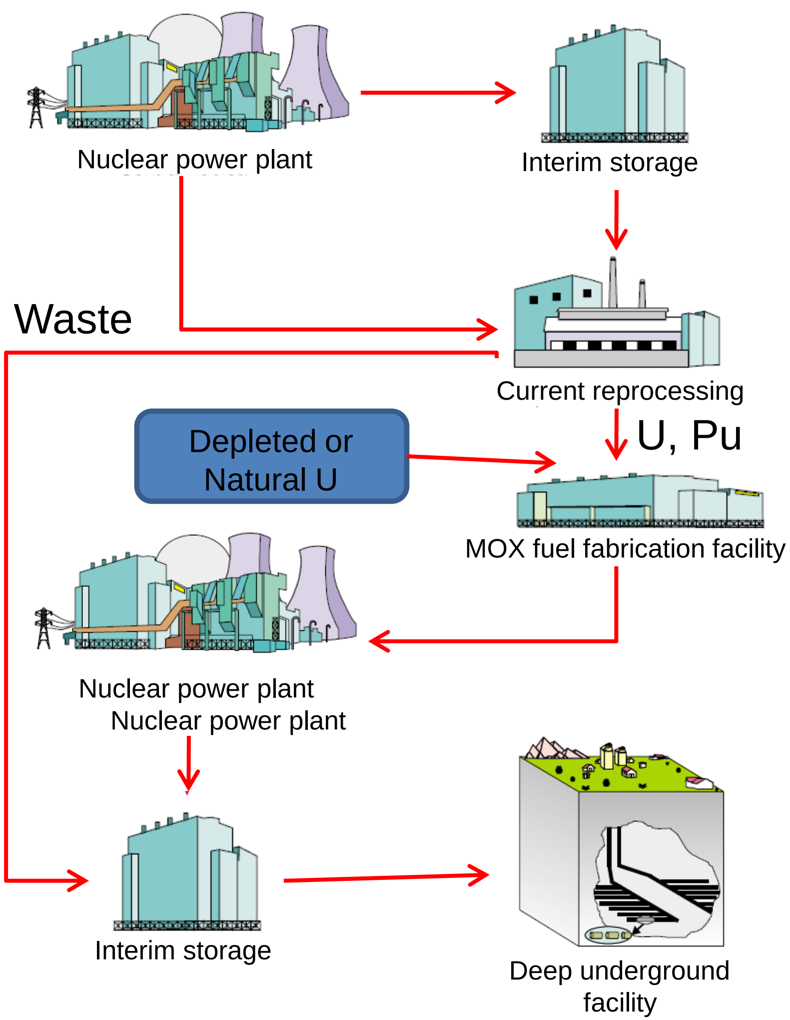
Nuclear fuel cycle options



Open cycle



Open cycle with reuse of Pu

Open cycle with reuse of Pu in thermal reactors

It increases the use of energy/resources up to 30%, reducing lightly (10%) the generation of waste.

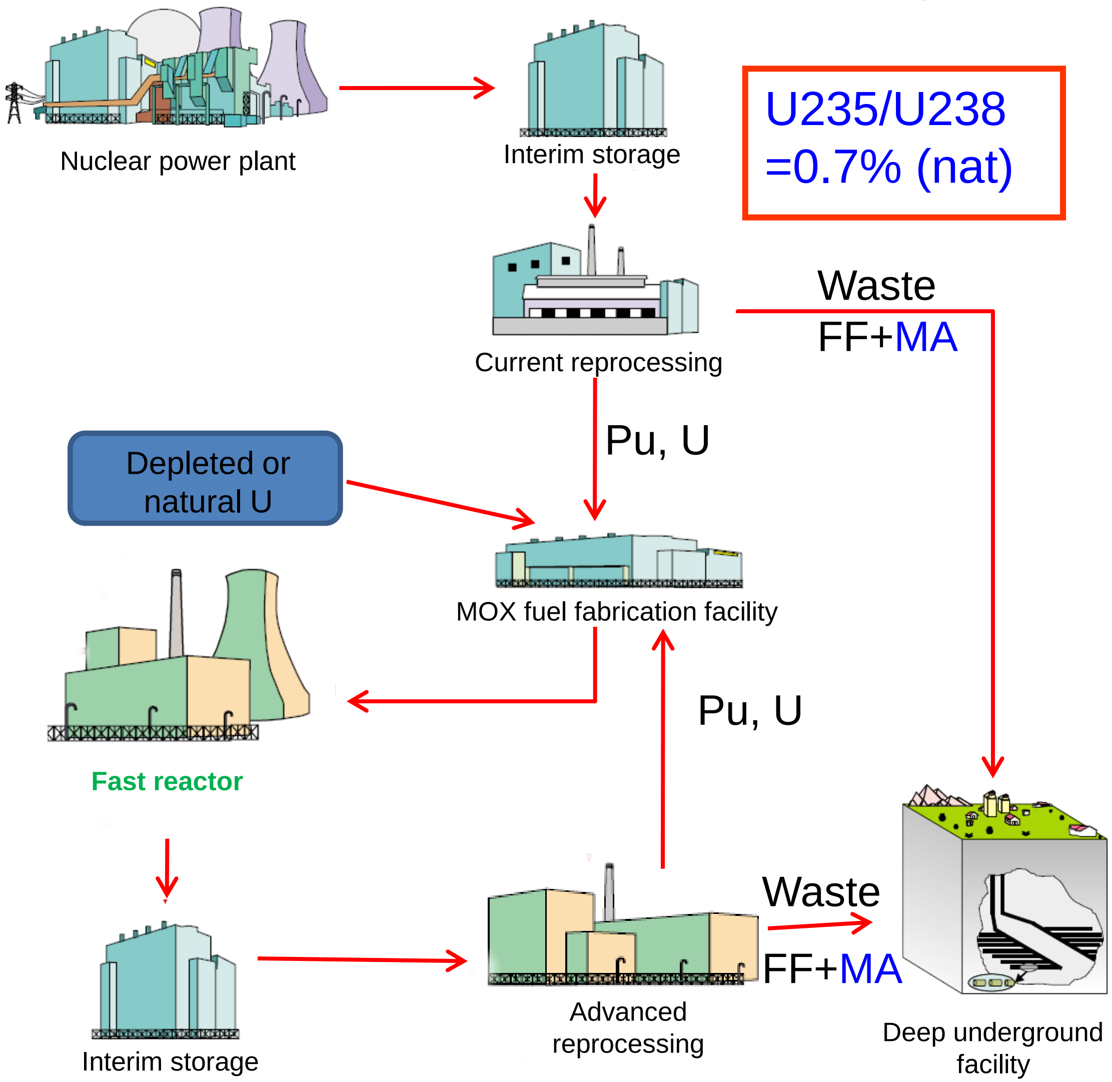
MOX technology available and proven. Performed successfully in several countries.

Limited to a fraction of MOX in the core due to degradation of safety (absorption in Pu240). EPR are able to use MOX in the whole core.

Difficulty for repeating the cycle due to degradation of Pu isotopic vector. Problems in neutronic, reprocessing, and final waste.

⇒Fast Reactors

Nuclear fuel cycle options



Generation of Pu from U238, multirecycling of Pu & U

Fast reactors with
Pu+U multirecycling

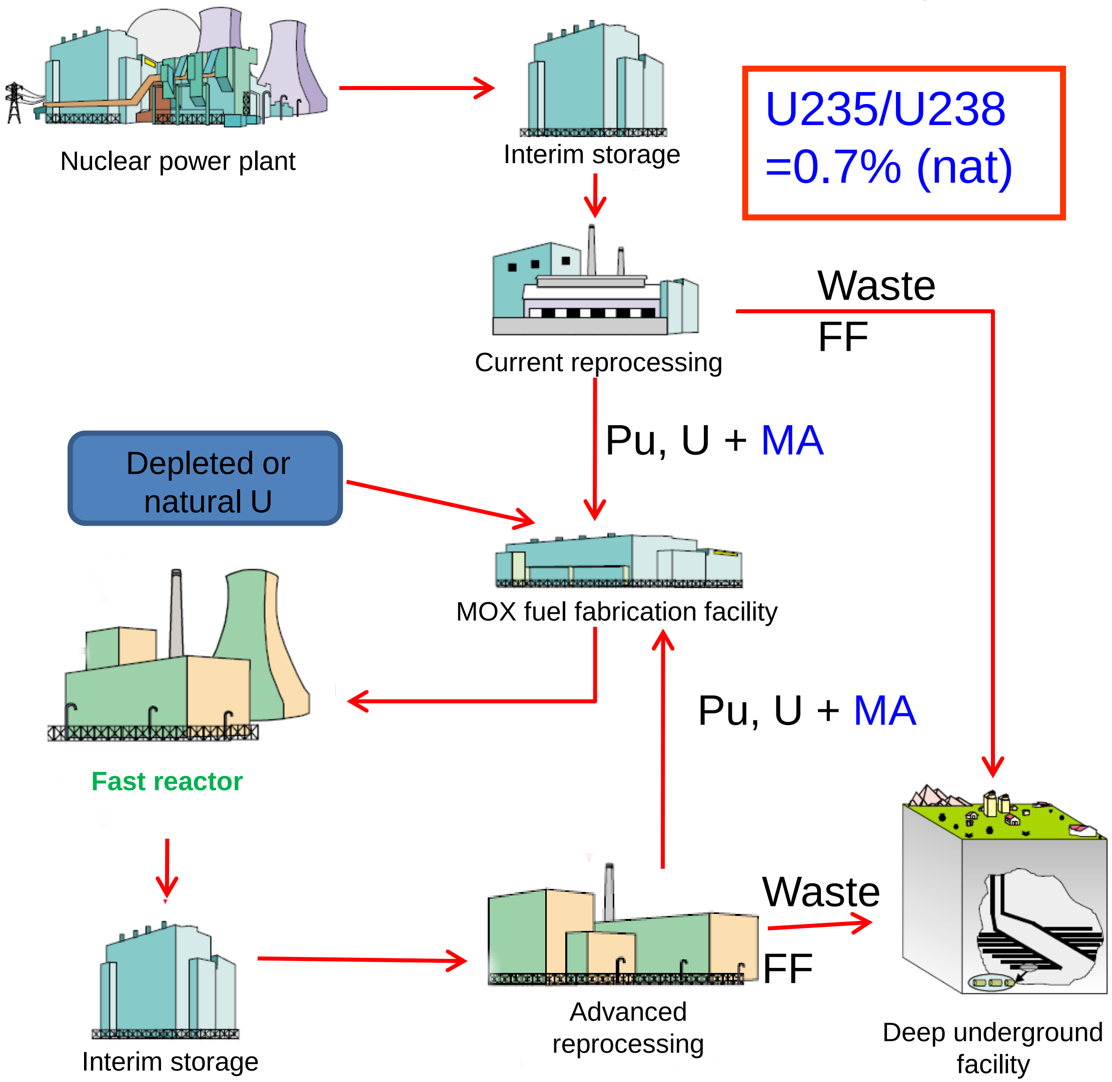
All the U-238 is burned, increasing the energy extracted in a factor 30-50.

If only Pu is recycled, high-level long-lived waste are reduced in a factor 10.

Technology already checked or available but can be improved.

With current prices of enriched U, reprocessing and fast reactors, they are not competitive, **but probably they will in the future**, and also competitive against other energy sources.

Nuclear fuel cycle options



Generation of Pu from U238, multirecycling of Pu & U & MA

Fast reactors with Pu+U+MA multirecycling

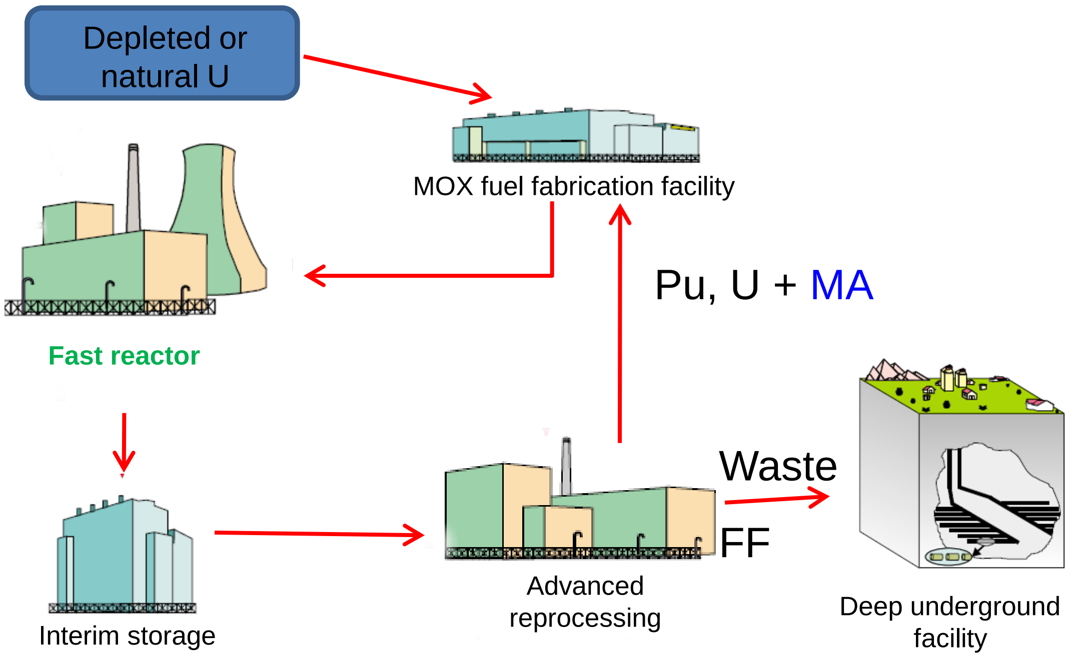
All the U-238 is burned, increasing the energy extracted in a factor 30-50.

If only Pu is recycled, high-level long-lived waste are reduced in a factor 10. With MA, the factor is 100.

In SFR, the MA content in the fuel is limited to 5% due to safety parameters.

With current prices of enriched U, reprocessing and fast reactors, they are not competitive, **but probably they will in the future**.

Nuclear fuel cycle transition



Generation of Pu from U238, multirecycling of Pu & U & MA

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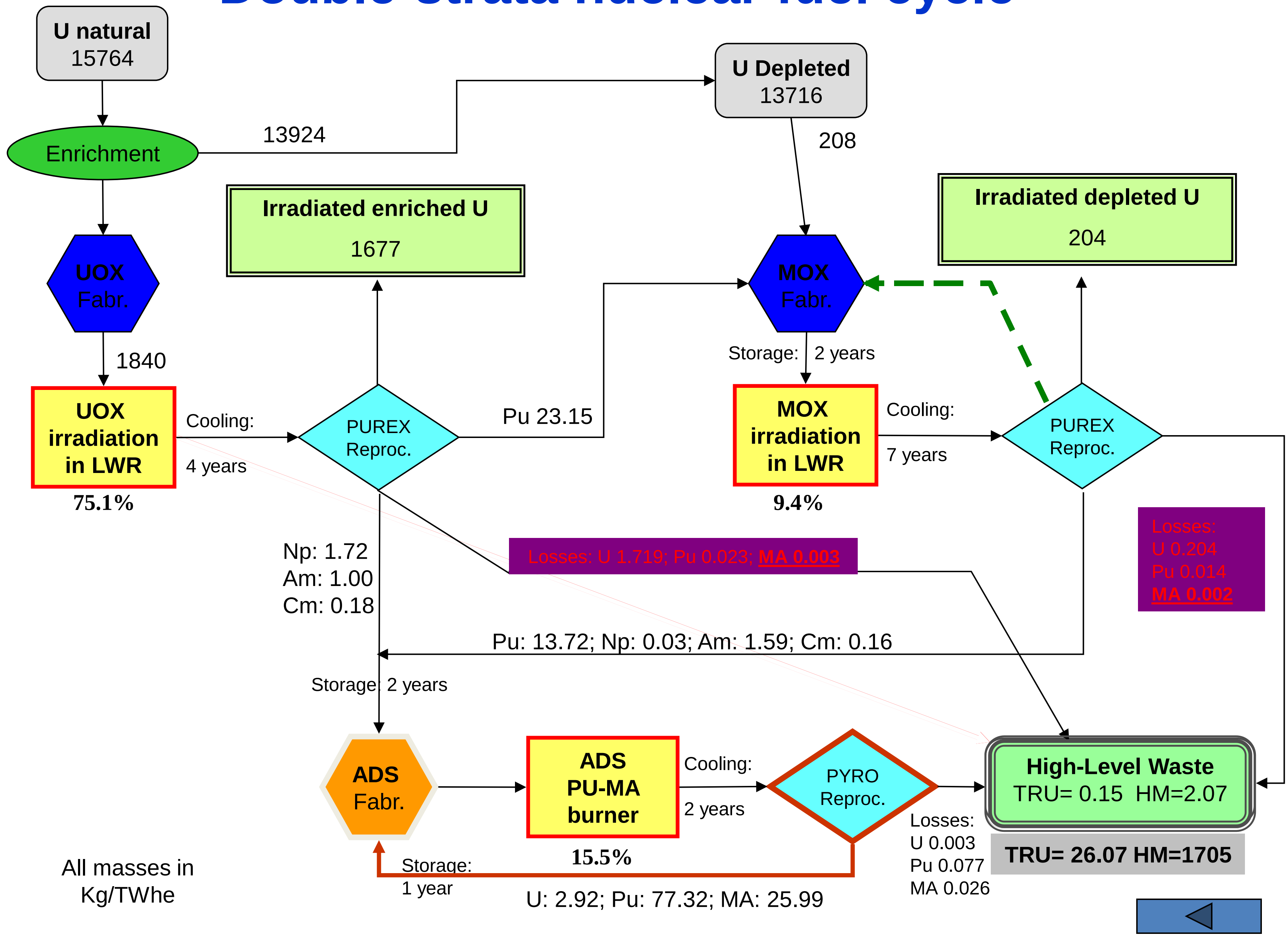
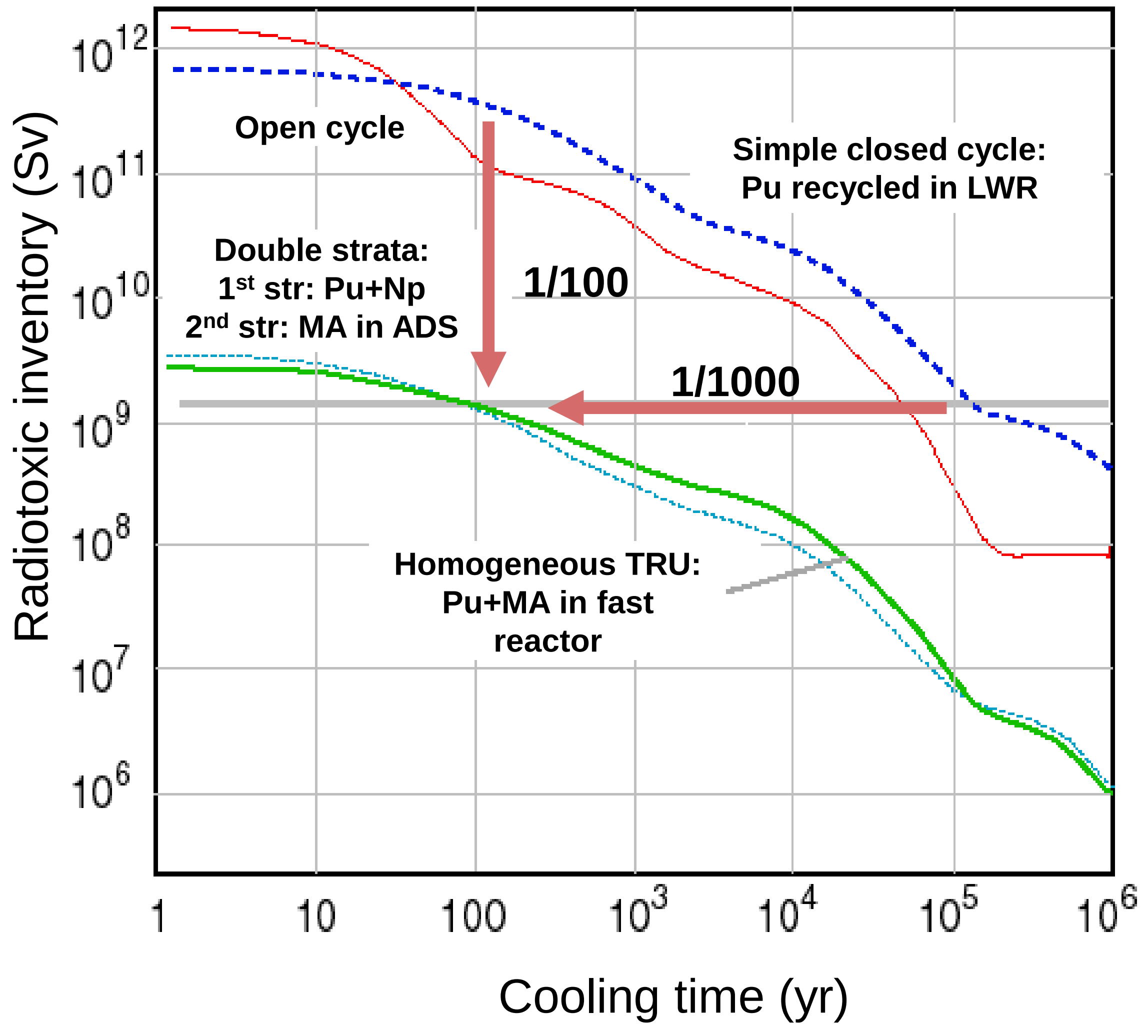
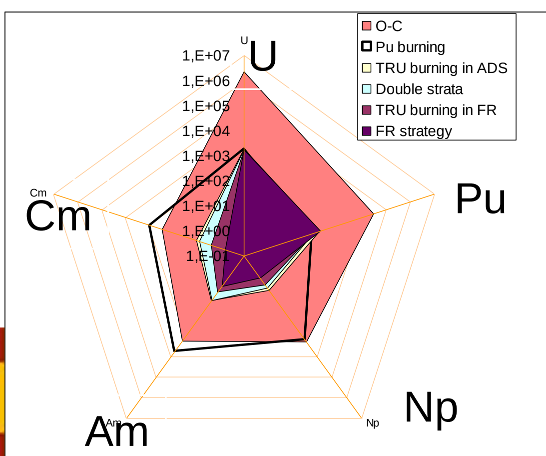
Double-strata nuclear fuel cycle



Impact of P&T


Radiotoxic inventory (Sv)
Cooling time (yr)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
1
10
100
10^{3}
10^{4}
10^{5}
10^{6}
Open cycle
Simple closed cycle:
Pu recycled in LWR
Double strata:
1st str: Pu+Np
2nd str: MA in ADS
1/100
1/1000
Homogeneous TRU:
Pu+MA in fast
reactor


O-C
Pu burning
TRU burning in ADS
Double strata
TRU burning in FR
FR strategy
1,E+07
1,E+06
1,E+05
1,E+04
1,E+03
1,E+02
1,E+01
1,E+00
1,E-01
U
Pu
Np
Am
Cm

HLW thermal power in scenarios with P&T

- **For an interim storage of 50 years, the thermal power of the high-level waste (HLW) is dominated by Pu and MA in scenarios without P&T. Heat evolution is slow and it takes:**

  ~ 1000 years to decrease in a factor 10 and

  ~ 10000 years, in a factor 100.

- **On the other hand, for scenarios with total recycling of Pu and MA, the HLW thermal power is dominated by fission products (mainly ^{90}Sr and ^{137}Cs and descendants) for 300 years.**

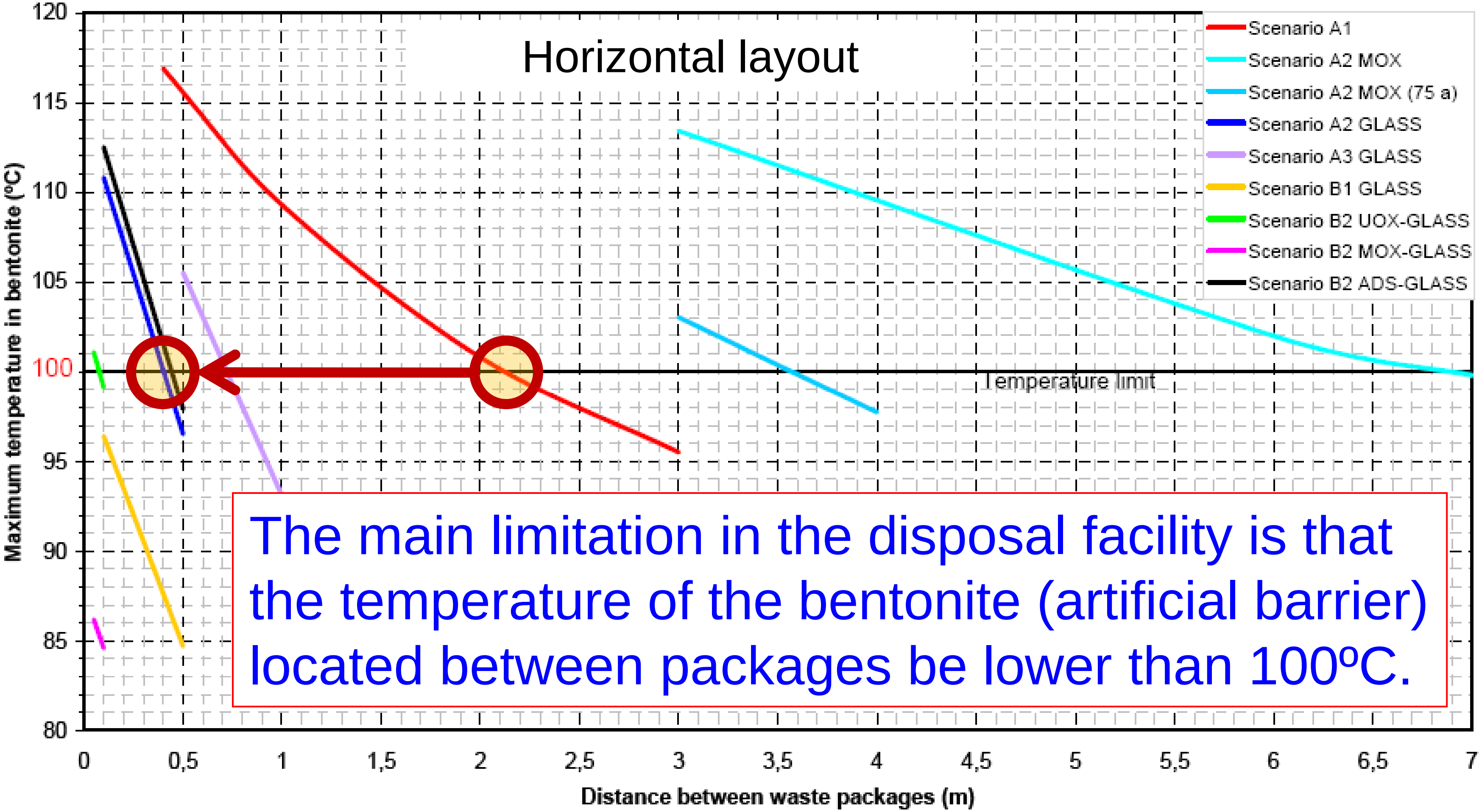
- **Hence, the thermal power of these scenarios is reduced in**

  a factor 10 in only 100 years and

  in more than a factor 100 in year 300 after discharge.

Distance between two waste packages

(granite Deep repository simulated by the EU Red-Impact project)



The main limitation in the disposal facility is that the temperature of the bentonite (artificial barrier) located between packages be lower than 100ºC.

Lower size of packages and lower distance -> size reduced!

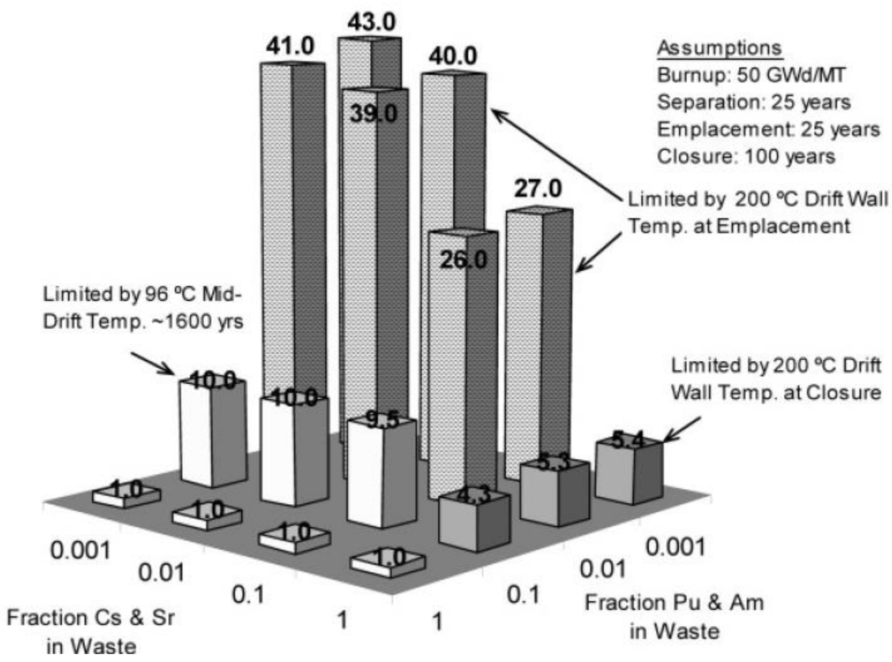
Thermal power in scenarios with P&T

- **For final disposals in hard rock formations, reductions in thermal power mean a reduction in the length of the galleries needed to store the HLW, leading to a reduction in the number of disposals or in their size.**

- **Gallery length reduction factors range between 1.5 and 6 depending on the specific formation.**

- **Larger reduction factors, 13 to 40, are achievable using a larger cooling time before disposal, or with an independent management of CS and Sr.**

- **Similar conclusions were achieved for Yucca Mountain.**



Yucca Mountain results

Contents

Conclusions

P&T is proposed internationally to ease the management of long-lived nuclear waste and reduce its long-term legacy by:

- Reducing the long-term radiotoxic inventory
- Reducing the time needed to achieve any level of reference in the radiotoxic inventory (factor 1/100 – 1/1000)
- Eliminating the risk of proliferation in the final disposal
- Reducing the volume needed to store the high-level waste
- Possibly simplifying the final disposal design
- Using the fission energy contained in the transuranic elements

Reducing long-term legacy:	Producing:	Needing:
High level waste mass (**1/20–1/1000**)	Electricity (**+30%-x30**)	Advanced technologies, potentially expensive and dangerous
Radiotoxicity (**1/100**)	Increase in the final disposal capacity (**x5-x40**)	***R&D to get the advantages without unacceptable costs***
Materials with possible military use (**1/100**)	Increase in the long-term prediction capacity	

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Thank you for your attention

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