Ciclo combustibile, scorie, accelerator driven system

M. Carta, C. Artioli

ENEA

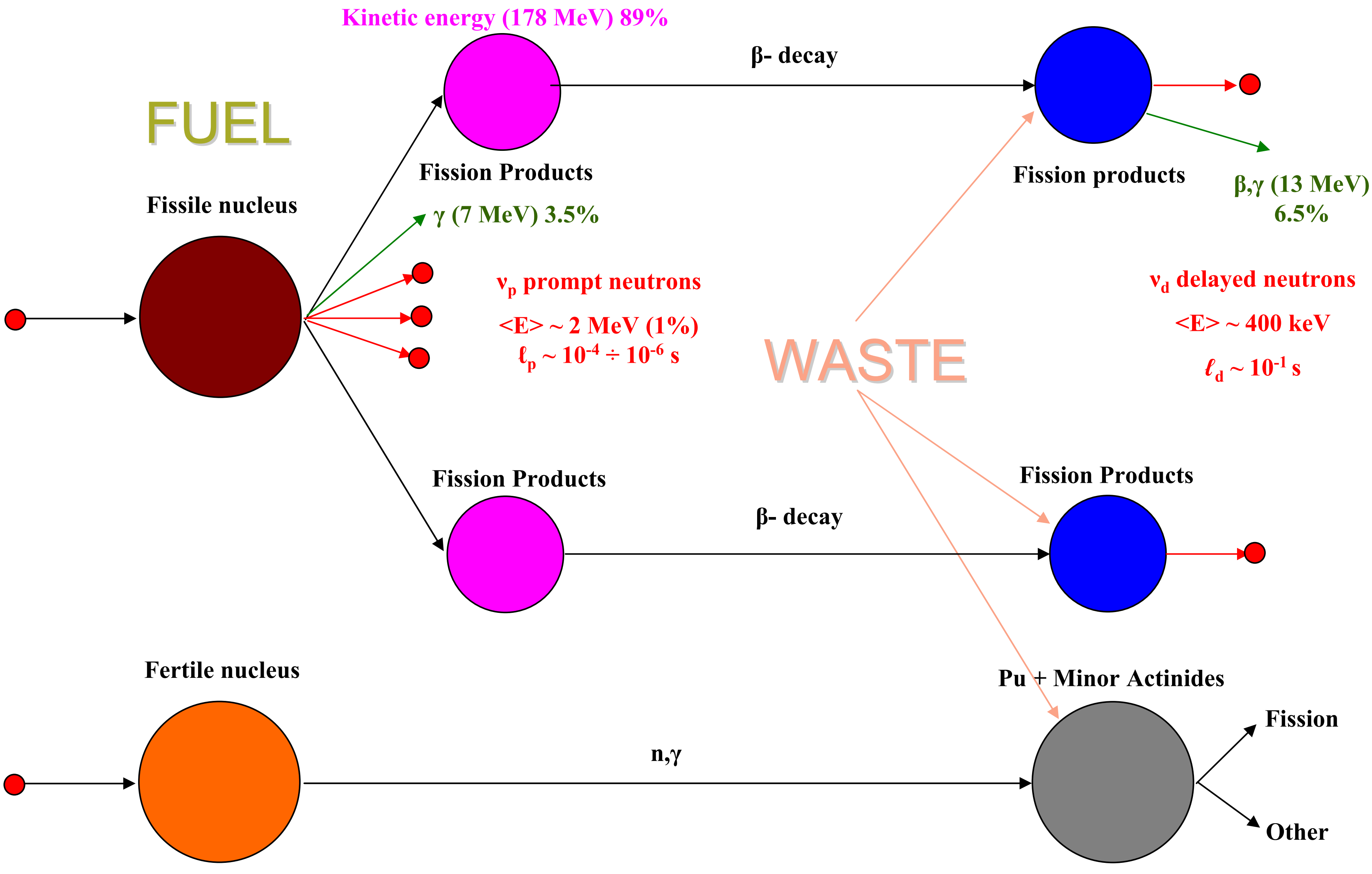
Fusione e Fissione Nucleare:

stato e prospettive sulle fonti energetiche nucleari per il futuro

INFN TORINO, 14 - 15 Dicembre 2009

Layout of the presentation

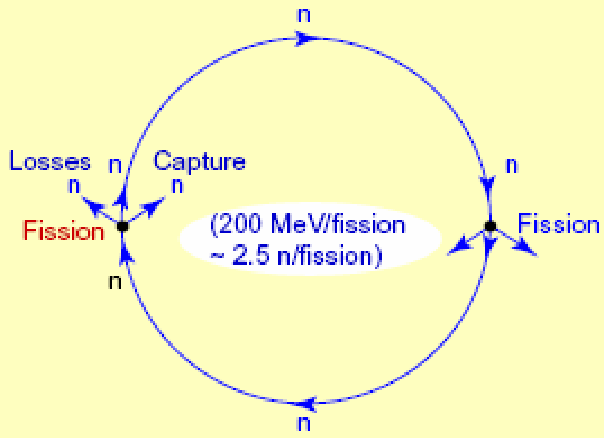
- Generalities (nuclear fission, chain reaction, Minor Actinides and Fission Products properties)
- Spent fuel characteristics (composition, radio-toxicity, MA and FP cross section examples)
- Basic fuel cycle options (once-through, Pu stocking, Pu recycling, extended Pu recycling)
- Fuel cycle schemes [scheme 1b, scheme 2a, scheme 3cV1, NEA study results, double strata scheme 3b, double strata scheme 3bV (variant)]
- ADS [basic concepts, inert matrix fuel, EFIT, the strategy (-42;0)]
- Conclusions



Kinetic energy (178 MeV) 89%
β- decay
FUEL
Fission Products
Fission products
β,γ (13 MeV) 6.5%
Fissile nucleus
γ (7 MeV) 3.5%
ν_p prompt neutrons
<E> ~ 2 MeV (1%)
$\ell_p \sim 10^{-4} \div 10^{-6}$ s
ν_d delayed neutrons
<E> ~ 400 keV
$\ell_d \sim 10^{-1}$ s
WASTE
Fission Products
Fission Products
β- decay
Fertile nucleus
Pu + Minor Actinides
Fission
n,γ
Other

Chain Reaction

Critical Reactor



Effective neutron multiplication factor

$$k = \frac{\text{Production}}{\text{Absorption + Losses}}$$

Self-sustained process:
k = 1
(if k < 1 the Reactor stops
if k > 1 the Reactor is supercritical)

⇒ The time derivative of the power kept equal to zero by control

Source

Y. Kadi, J.P. Revol

- The **minor actinides** are the actinide elements in used nuclear fuel other than uranium and plutonium, which are termed the major actinides.
- The minor actinides include neptunium, americium, curium, berkelium, californium, einsteinium, and fermium.
- The most important isotopes in spent nuclear fuel are **neptunium**-237, **americium**-241, americium-243, **curium**-242 through -248, and californium-249 through -252.

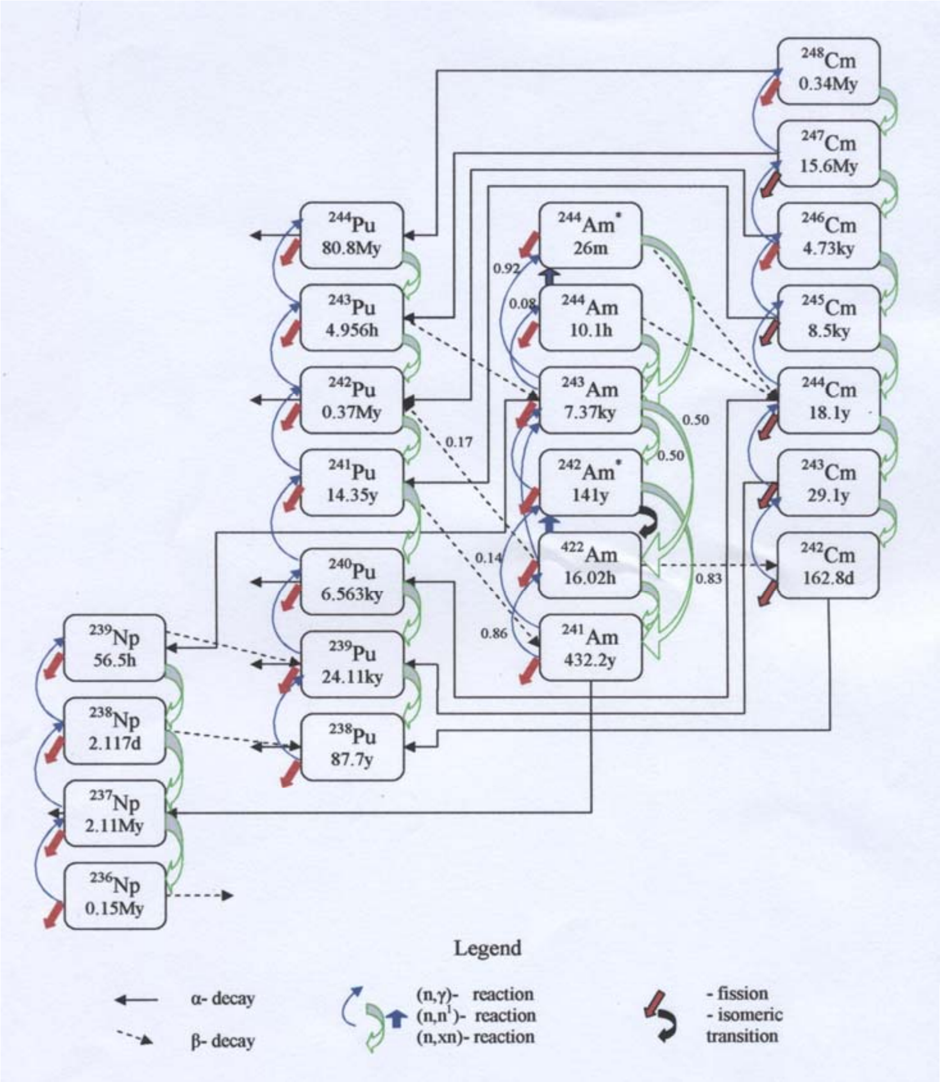


Fig. 1. Decay chains and reactions diagram

Chain reaction with minor actinides?

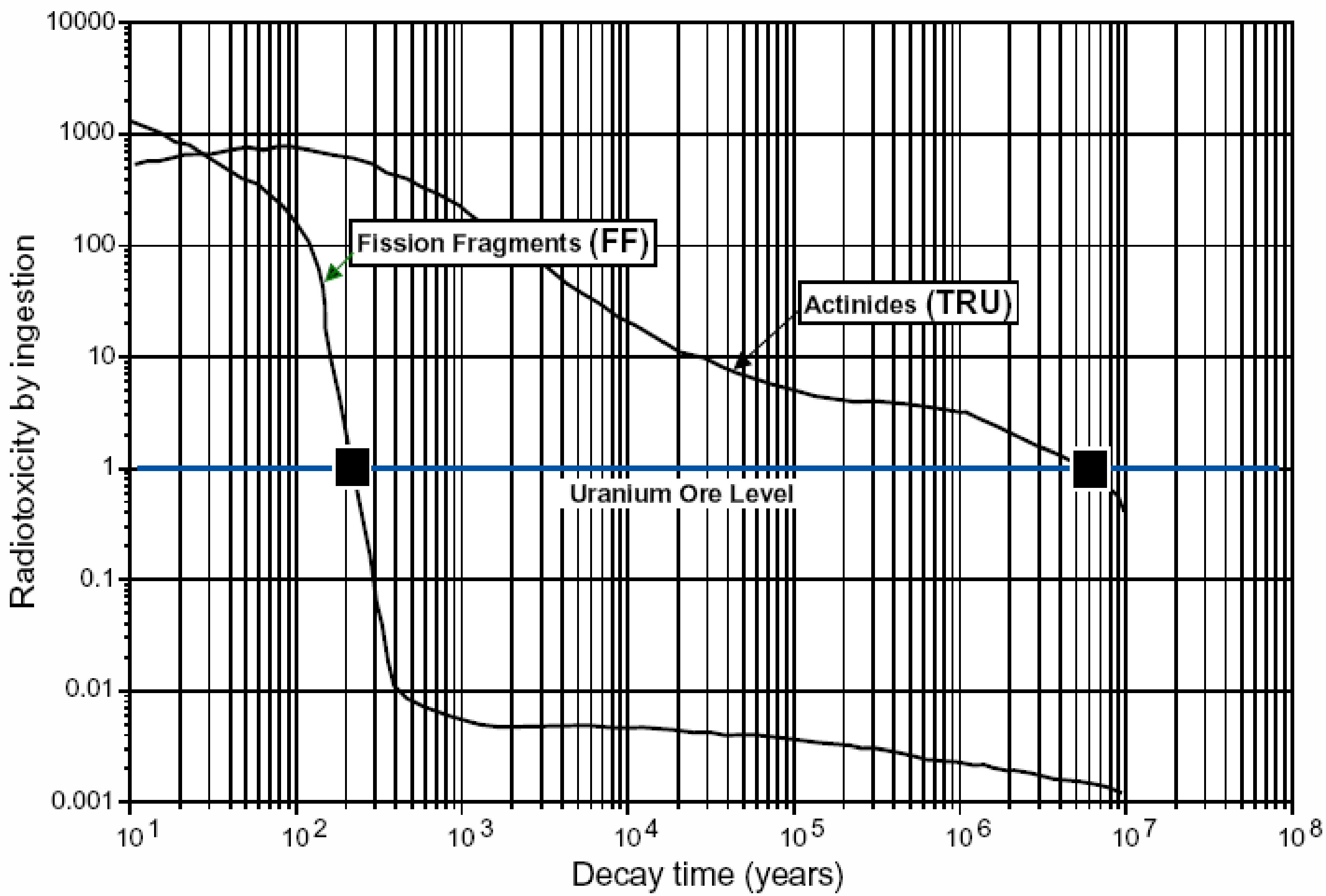
Uranium-235	Uranium-238	Plutonium-239	Americium-241	Curium-244
0.00650	0.0157	0.00200	0.00130	0.00130
$\beta = \nu_d/(\nu_p+\nu_d)$				

Actinides and fission products half-life

Actinides				Half-life	Fission products			
^{244}Cm	**^{241}Pu ^{f}**	^{250}Cf	**^{243}Cm ^{f}**	**10–30 y**	^{137}Cs	^{90}Sr	^{85}Kr	
^{232}U ^{f}		^{238}Pu		**69–90 y**			^{151}Sm	
Thorium series	**^{249}Cf ^{f}**	**^{242}Am ^{f}**		**141–351 y**				
	^{241}Am		**^{251}Cf ^{f}**	**431–898 y**				
^{240}Pu	^{229}Th	^{246}Cm	^{243}Am	**$5–7 \cdot 10^{3}$ y**				
Thorium series	**^{245}Cm ^{f}**	^{250}Cm	**^{239}Pu ^{f}**	**$8–24 \cdot 10^{3}$ y**				
	^{233}U ^{f}	^{230}Th	^{231}Pa	**$32–160 \cdot 10^{3}$ y**				
	Neptunium series	^{234}U	Actinium series	**$211–290 \cdot 10^{3}$ y**	^{99}Tc		^{126}Sn	^{79}Se
^{248}Cm		^{242}Pu		**$340–373 \cdot 10^{3}$ y**	Long-lived fission products			
	^{237}Np	Radium series		**$1–2 \cdot 10^{6}$ y**	^{93}Zr	^{135}Cs		
^{236}U	Neptunium series		**^{247}Cm ^{f}**	**$6–23 \cdot 10^{6}$ y**		^{107}Pd	^{129}I	
^{244}Pu				**$80 \cdot 10^{6}$ y**				
^{232}Th		^{238}U	**^{235}U ^{f}**	**$0.7–12 \cdot 10^{9}$ y**				

	Before	After
Uranium	100.0%	93.40%
Enrichment	4.2%	0.71%
Plutonium	0.0%	1.27%
Minor Actinides	0.0%	0.14%
Fission products	0.0%	5.15%

Heavy metal composition of 4.2% enriched nuclear fuel before and after 40 GWD/MTU. Minor actinides include neptunium, americium, and curium.

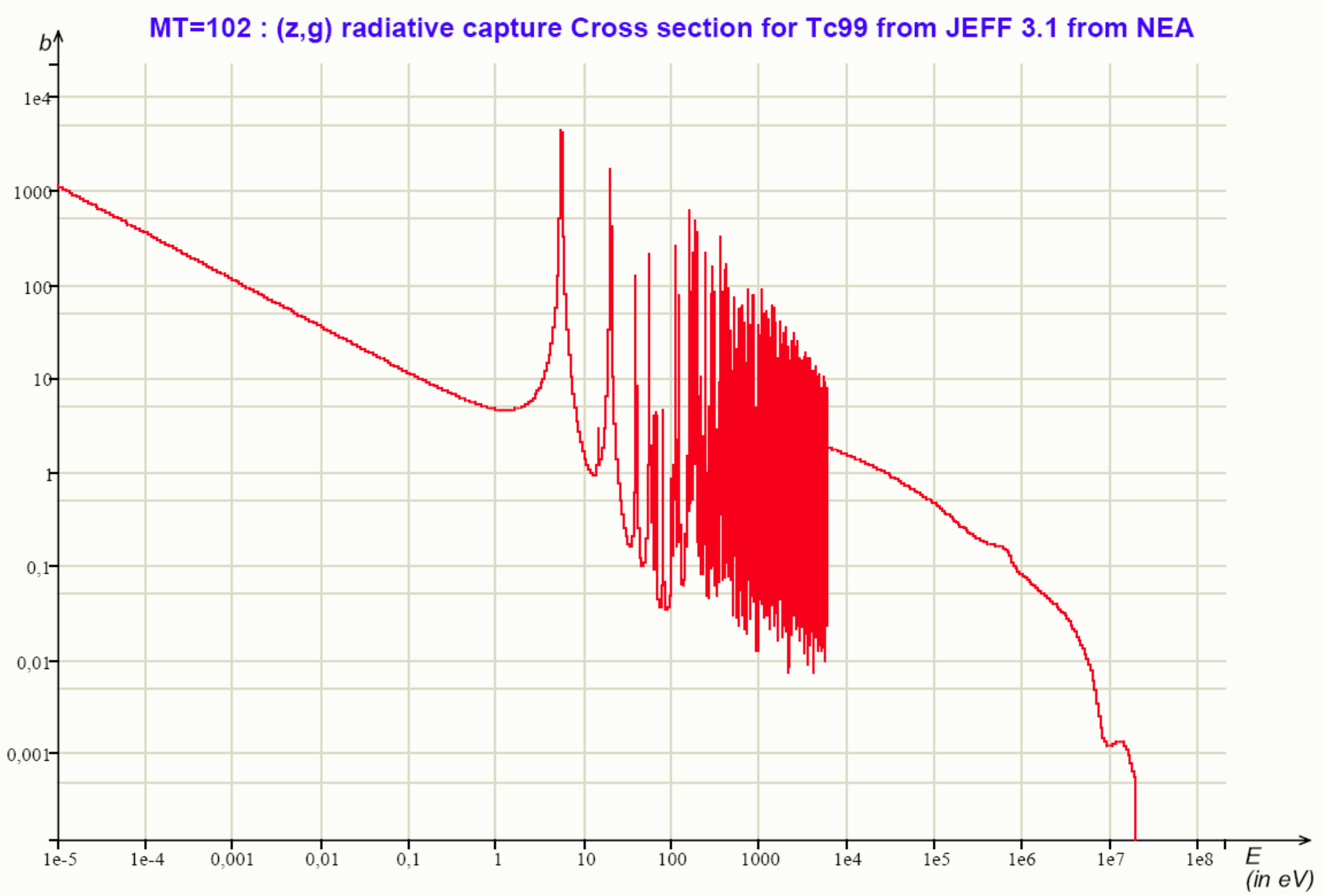


Time evolution of the potential radio-toxicity (relative to uranium ore) of the two main components of nuclear waste for PWR spent fuel.

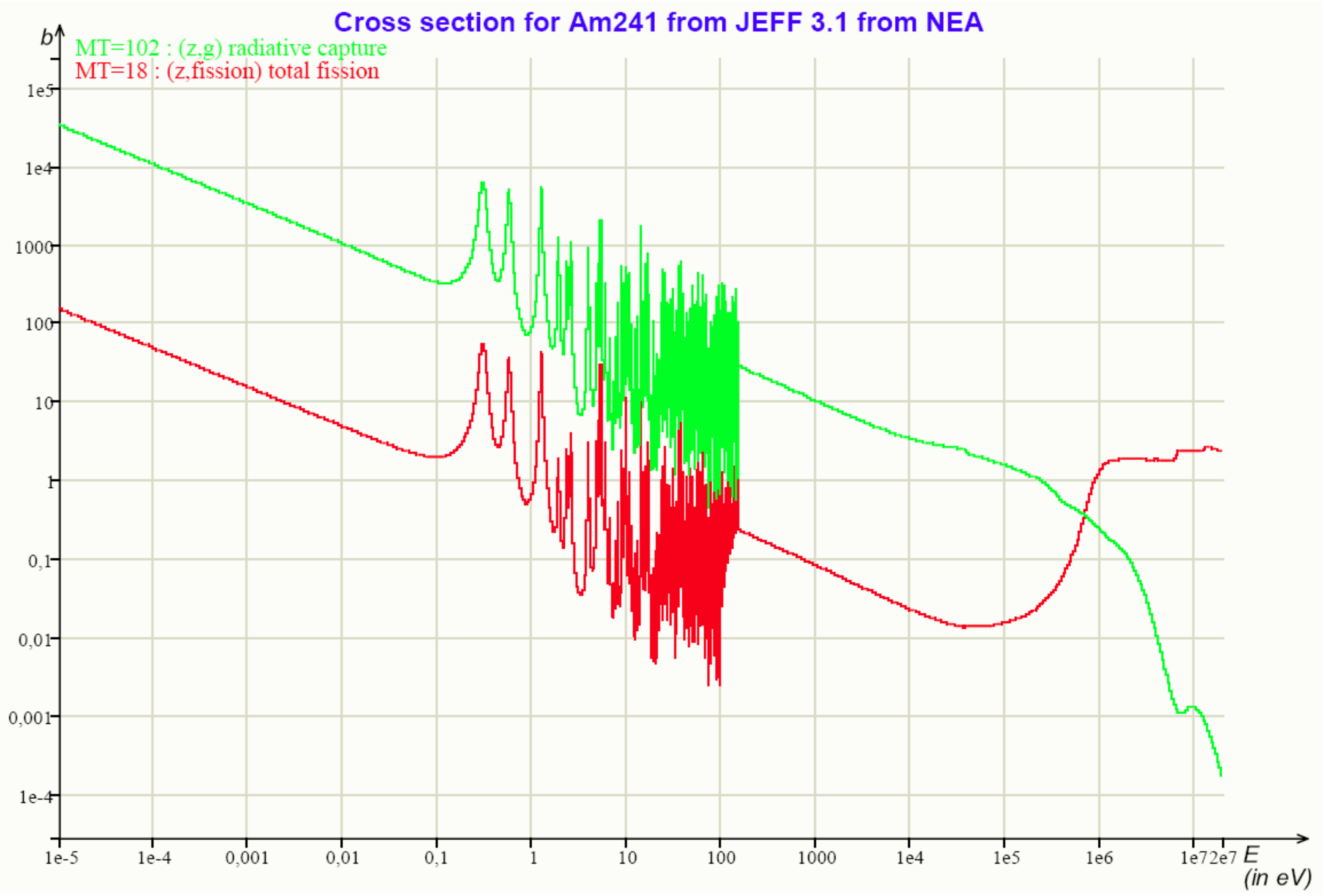
Source Y. Kadi, J.P. Revol

The 7 long-lived Fission Products

Prop:	t½	Yield
Unit:	Ma	%
^{99}Tc	0.211	6.1385
^{126}Sn	0.230	0.1084
^{79}Se	0.295	0.0447
^{93}Zr	1.53	5.4575
^{135}Cs	2.3	6.9110
^{107}Pd	6.5	1.2499
^{129}I	15.7	0.8410

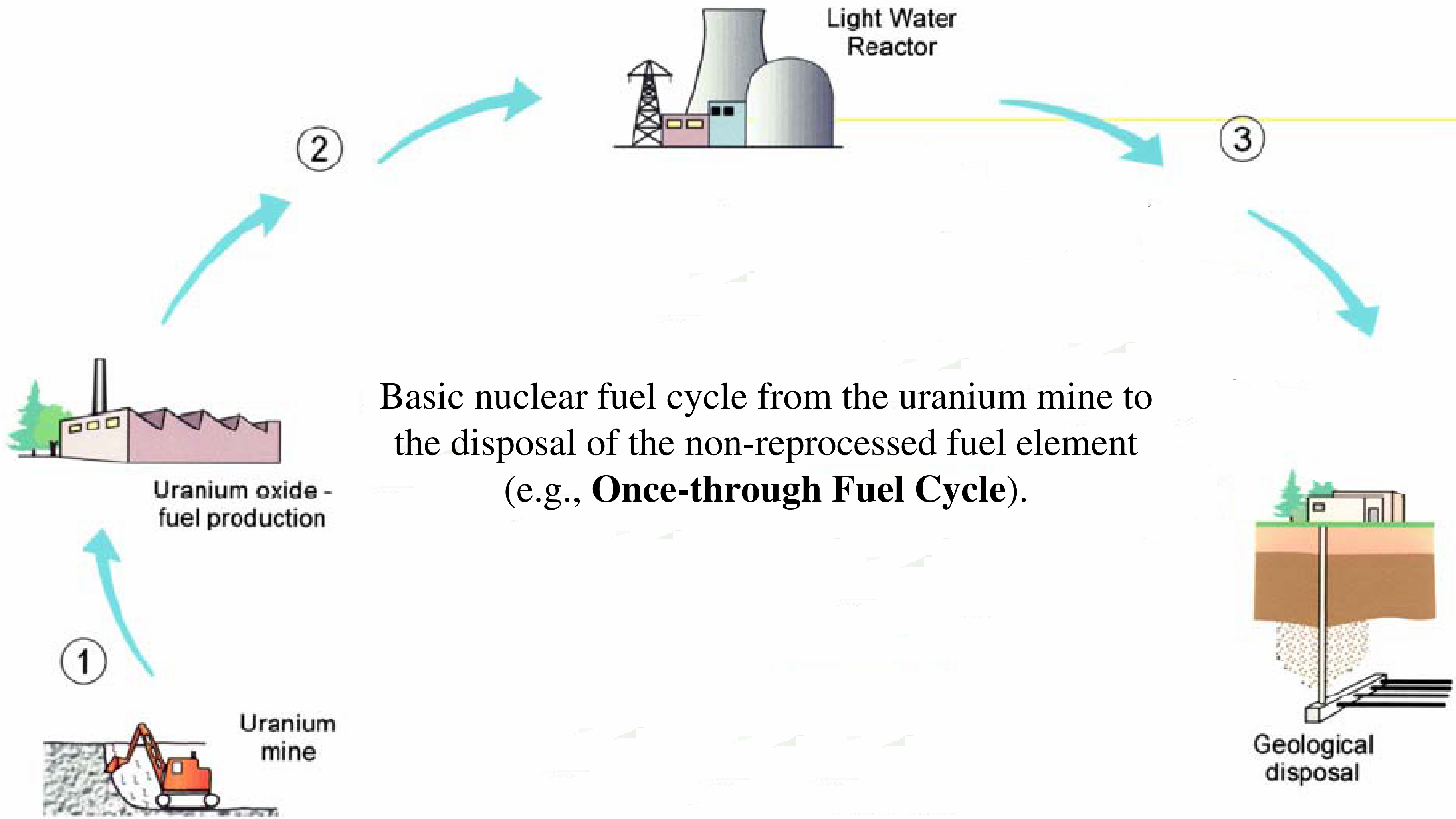


FP can only be destroyed by neutron capture



MA can only be destroyed by fission

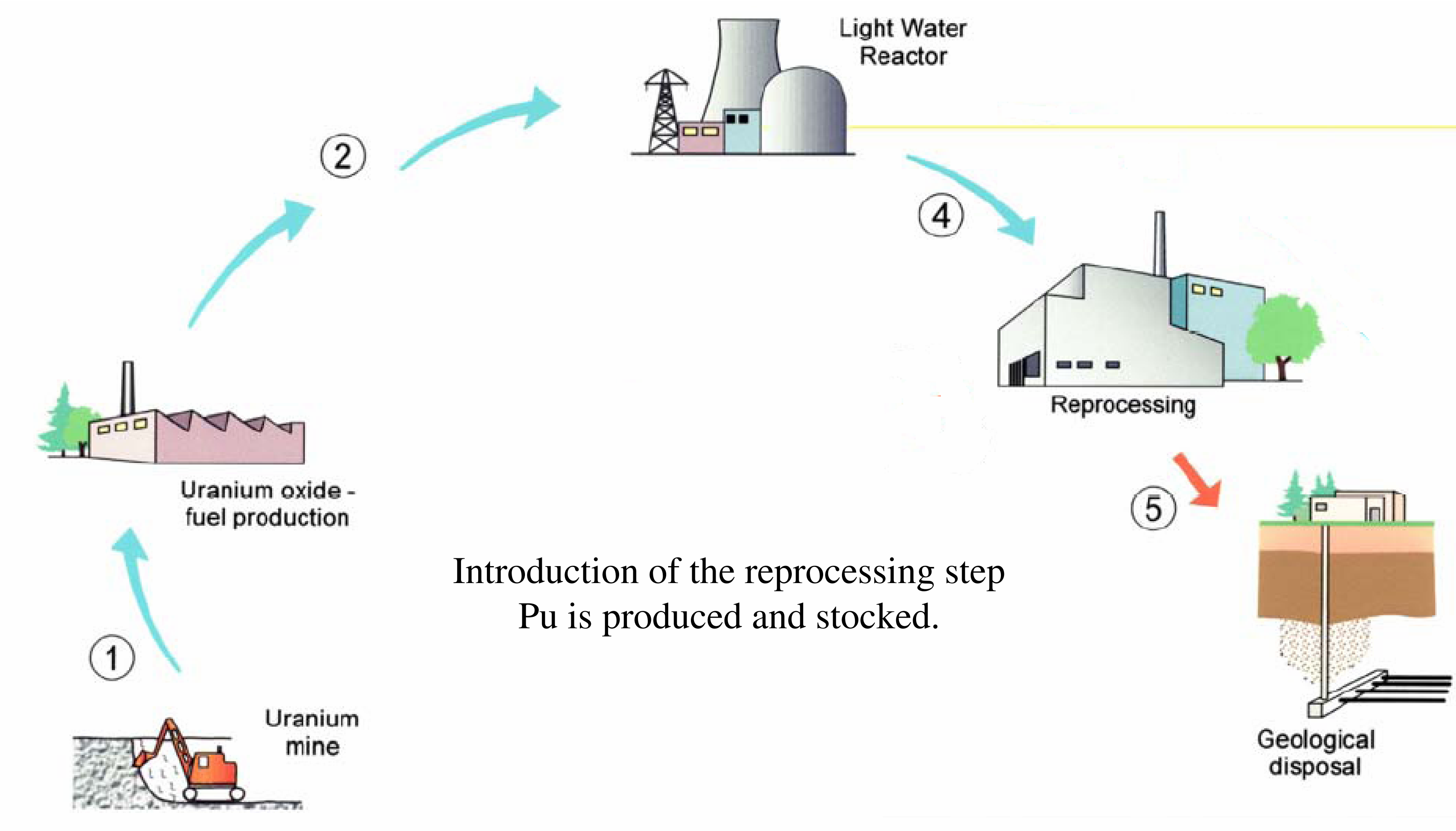
Basic fuel cycle options



Basic nuclear fuel cycle from the uranium mine to the disposal of the non-reprocessed fuel element (e.g., **Once-through Fuel Cycle**).

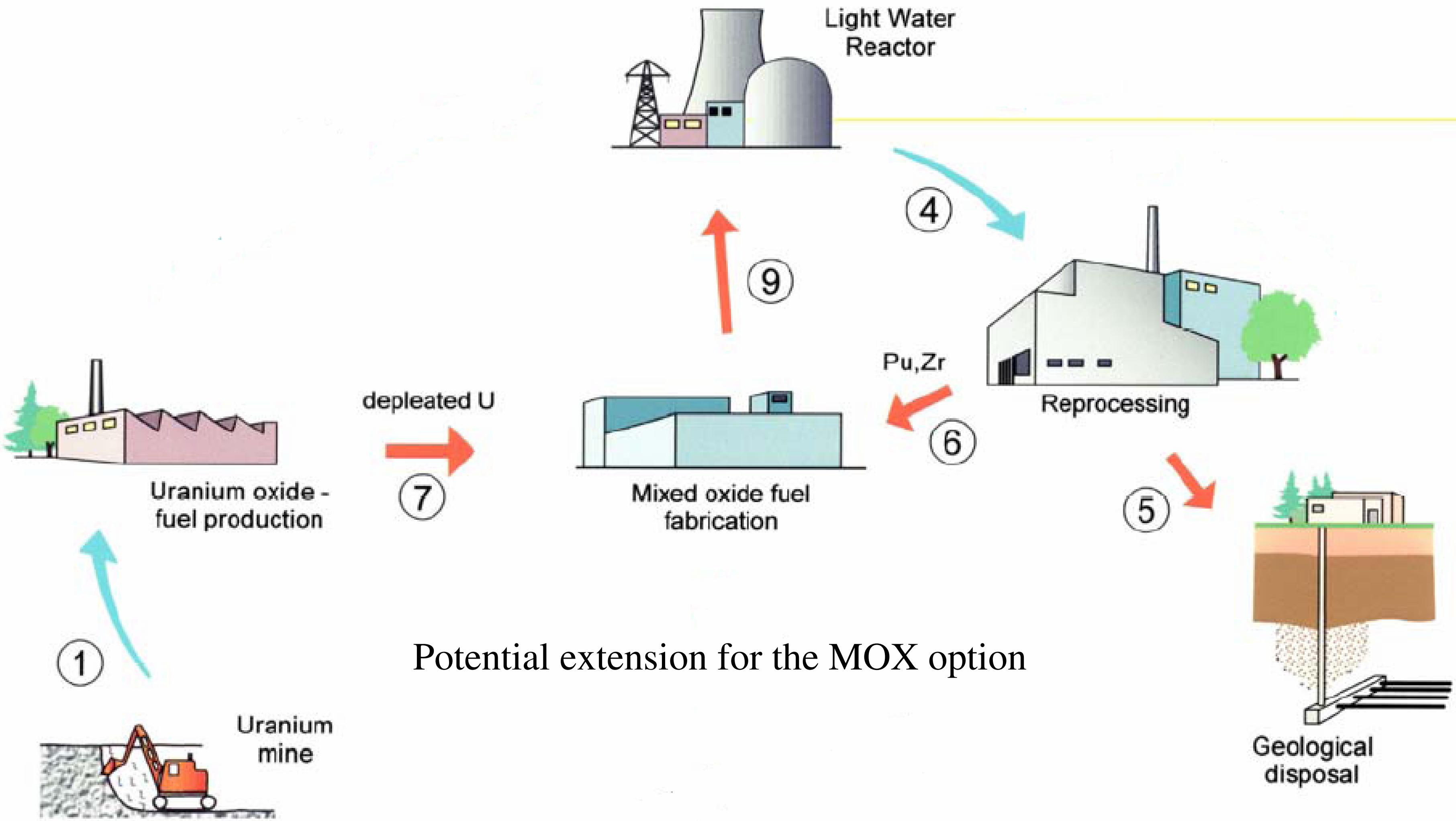
Basic fuel cycle options

Pu stocking



Introduction of the reprocessing step
Pu is produced and stocked.

Pu recycling



Potential extension for the MOX option

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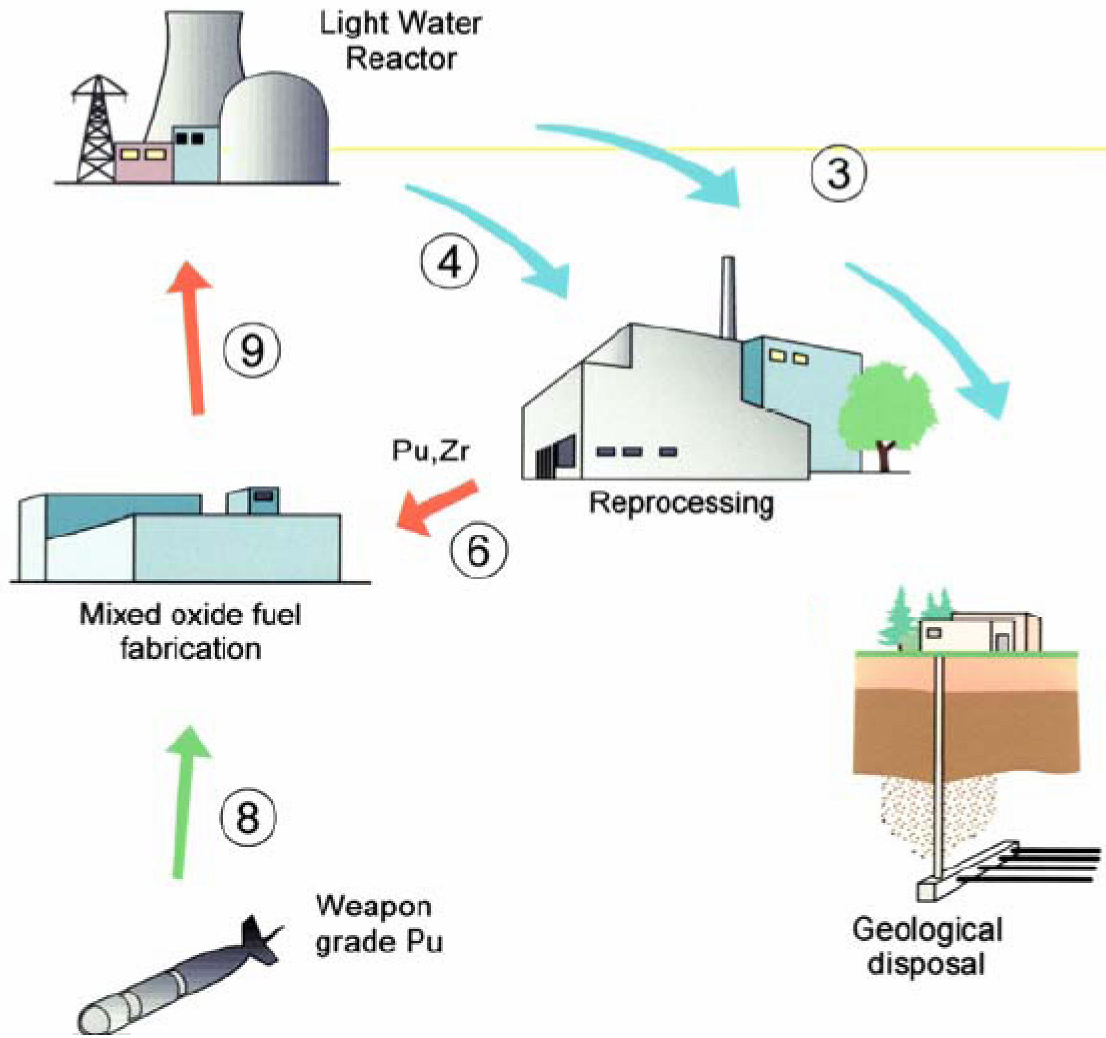
Extended Pu recycling



Fuel cycle extension. It includes spent U-fuel reprocessing, plutonium fuel fabrication (U-free), Pu burning in the reactor, intermediate storage and direct geological disposal of the rock-like spent fuel.

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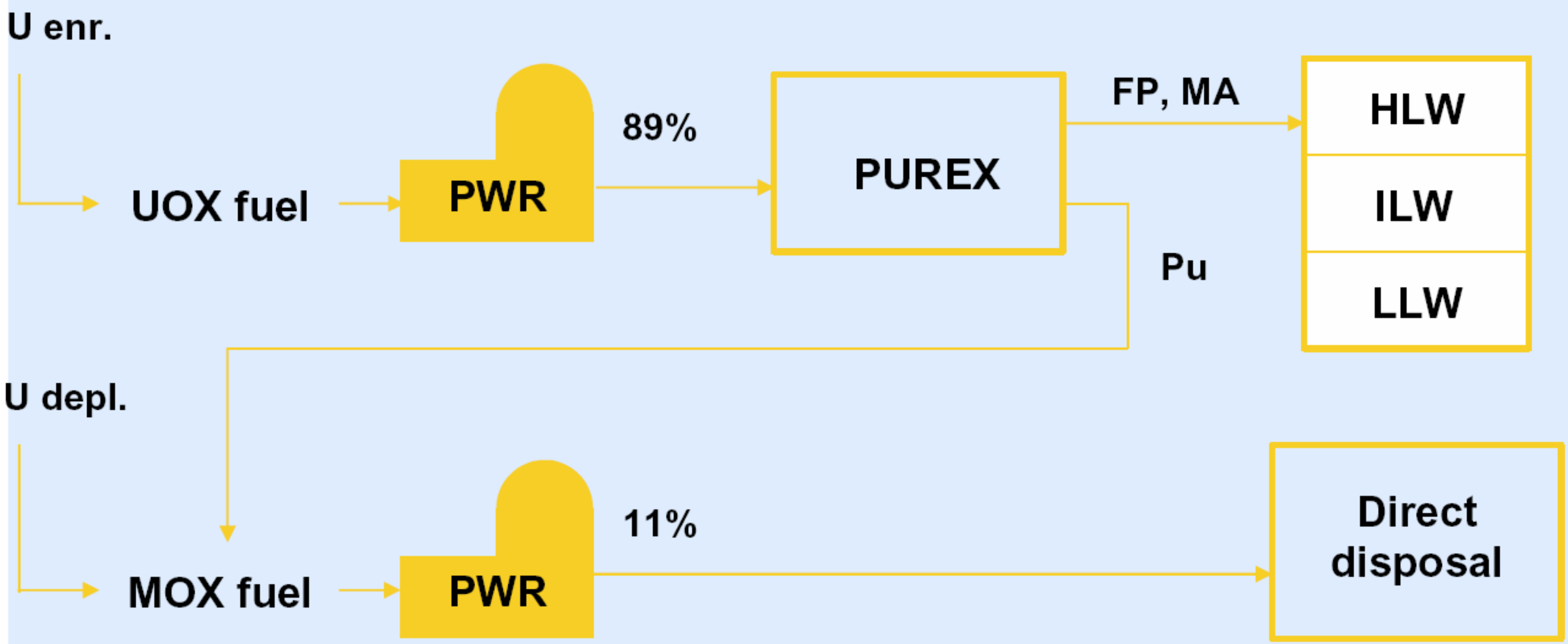
Present industrial practice

Scheme 1b PUREX reprocessing fuel cycle

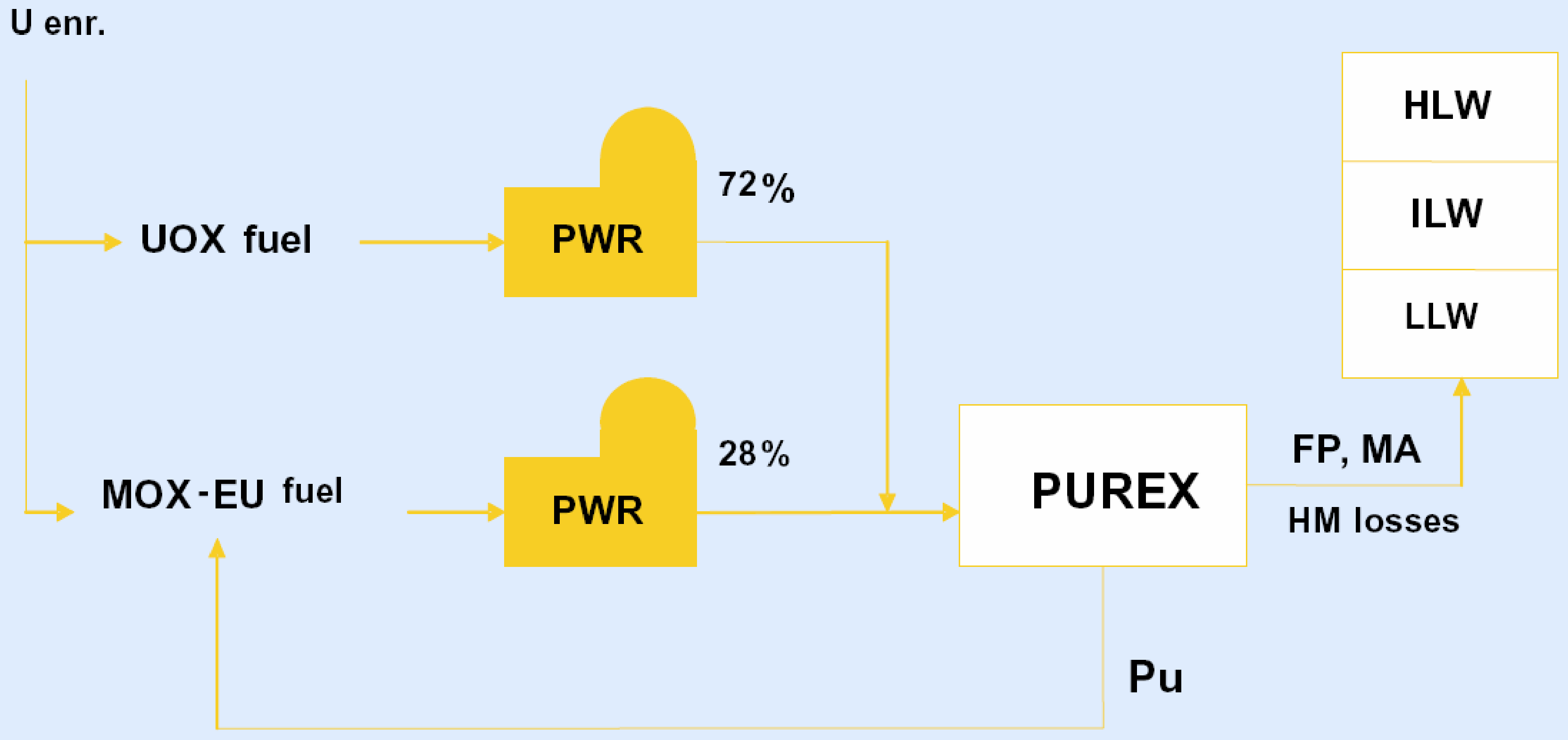
Plutonium is recycled once in the form of MOX.



Partially closed cycle

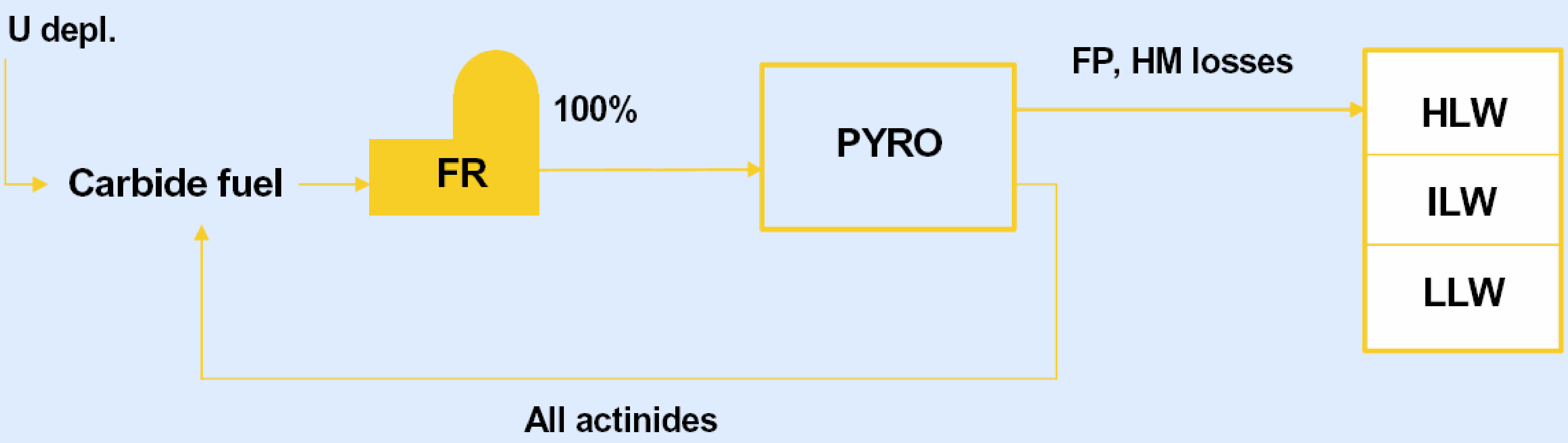
Scheme 2a : Plutonium burning in LWR

Uses LWRs only. Requires MOX fuel with enriched uranium (MOX-EU).

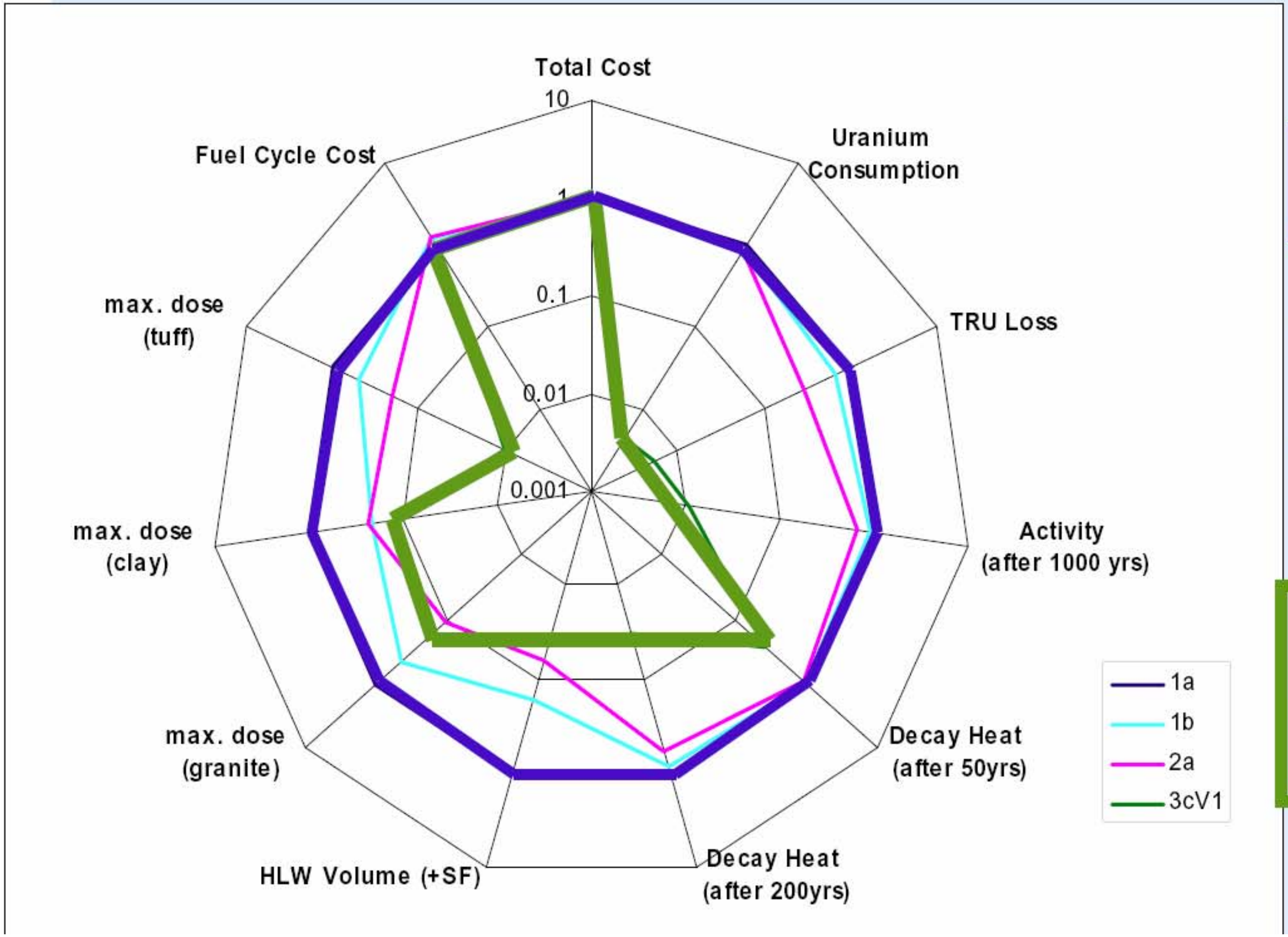


Fully closed cycle, all Actinides

Scheme 3cV1 All-FR strategy *Based on Gen-IV gas-cooled fast reactor*



Main results of NEA study (2006)



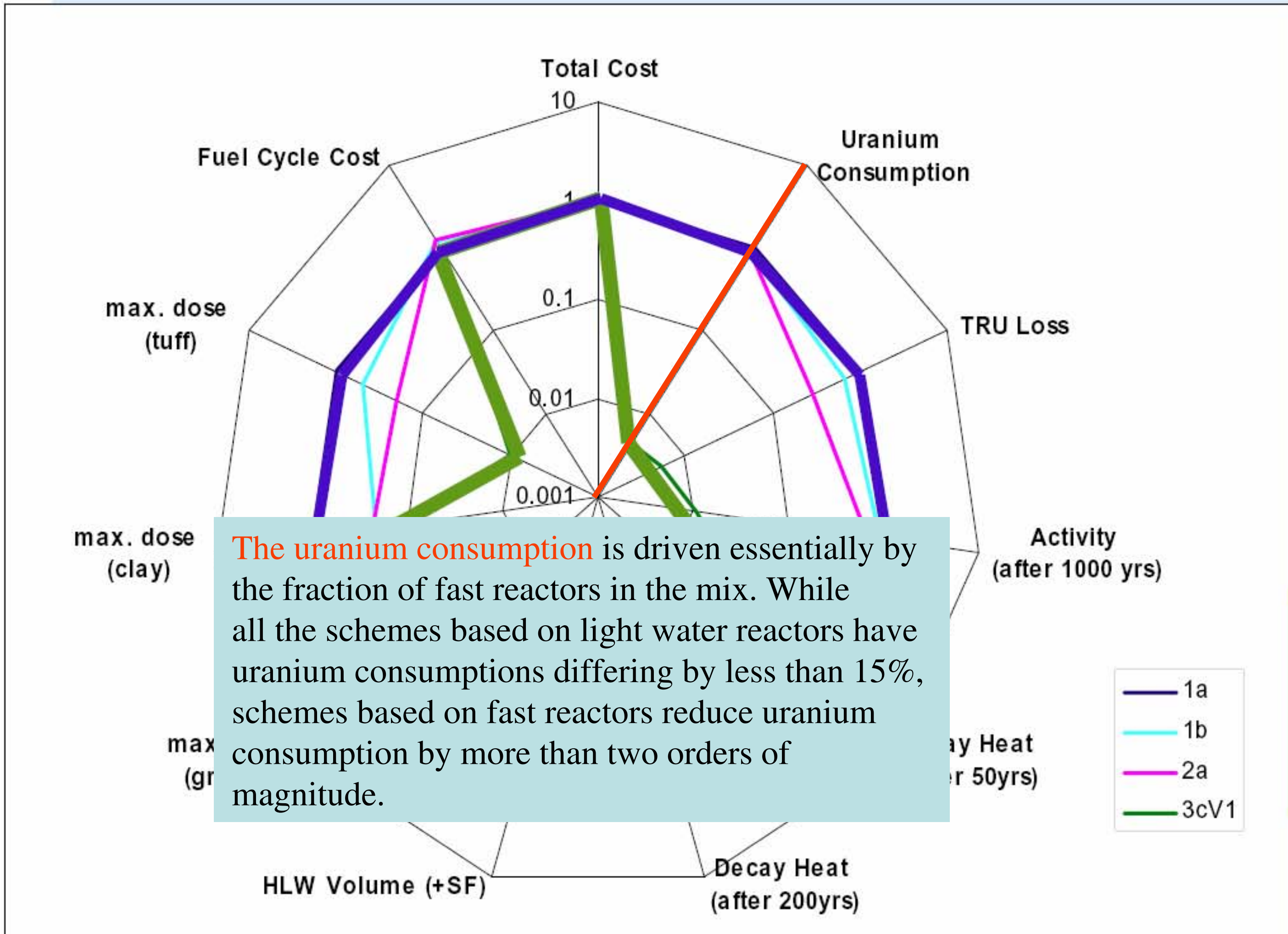
1a Once-through cycle as reference.

1b: full LWR park, Pu re-used once

2a: full LWR park, multiple re-use of Pu

3cV1: full fast reactor park and fully closed fuel cycle.

Main results of NEA study (2006)



The uranium consumption is driven essentially by the fraction of fast reactors in the mix. While all the schemes based on light water reactors have uranium consumptions differing by less than 15%, schemes based on fast reactors reduce uranium consumption by more than two orders of magnitude.

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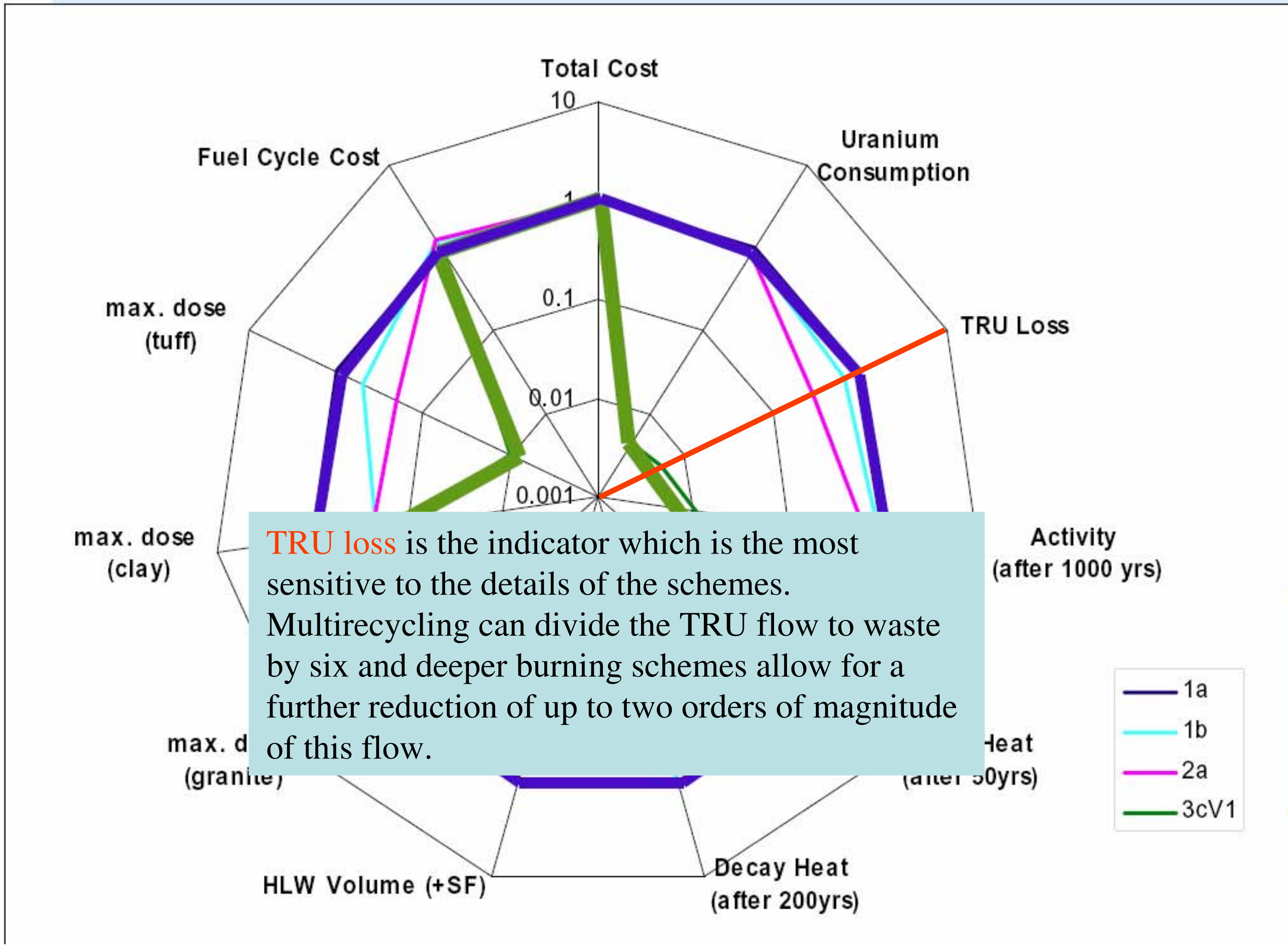
Main results of NEA study (2006)



TRU loss is the indicator which is the most sensitive to the details of the schemes. Multirecycling can divide the TRU flow to waste by six and deeper burning schemes allow for a further reduction of up to two orders of magnitude of this flow.

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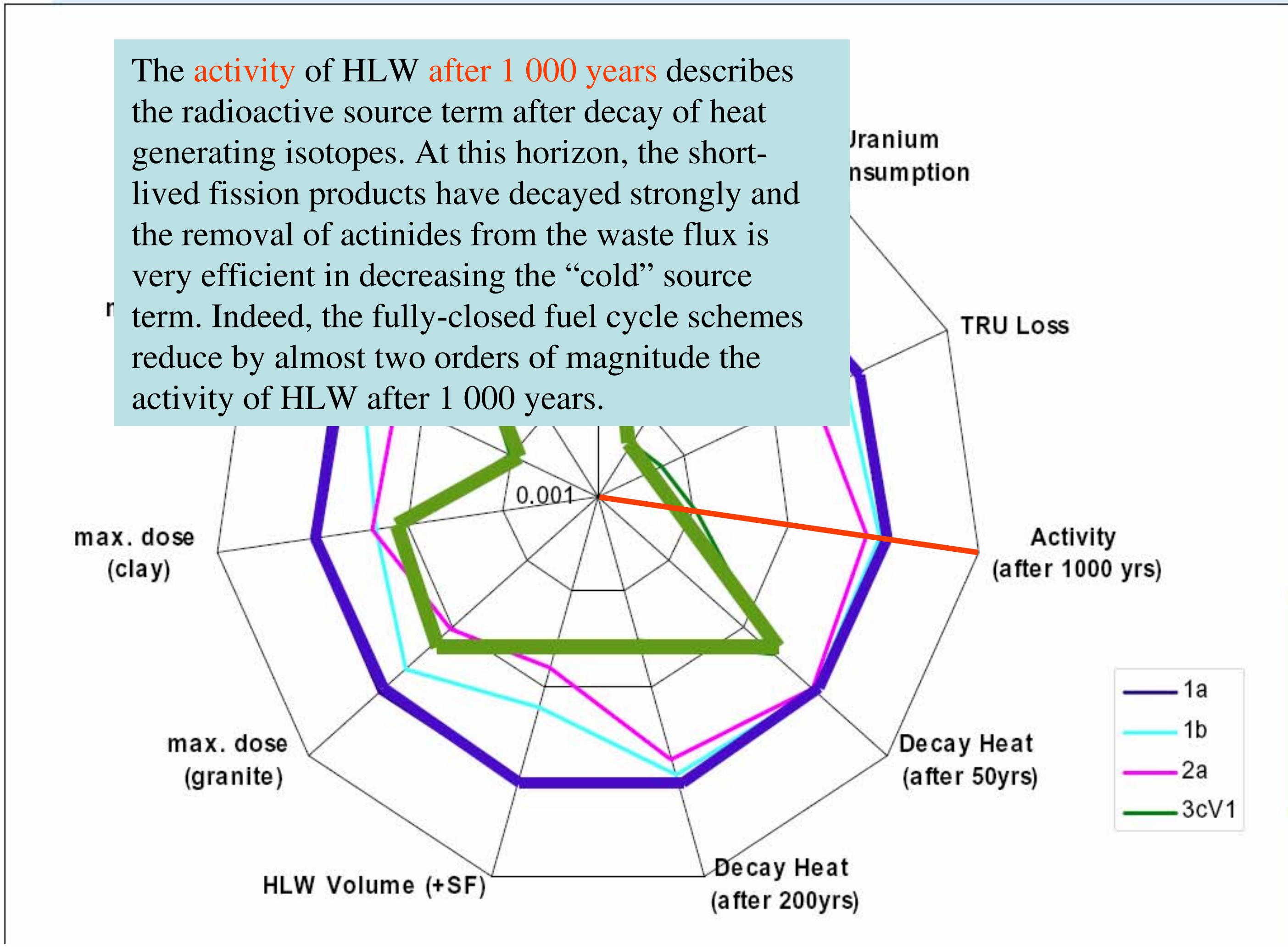
Main results of NEA study (2006)

The activity of HLW after 1 000 years describes the radioactive source term after decay of heat generating isotopes. At this horizon, the short-lived fission products have decayed strongly and the removal of actinides from the waste flux is very efficient in decreasing the "cold" source term. Indeed, the fully-closed fuel cycle schemes reduce by almost two orders of magnitude the activity of HLW after 1 000 years.



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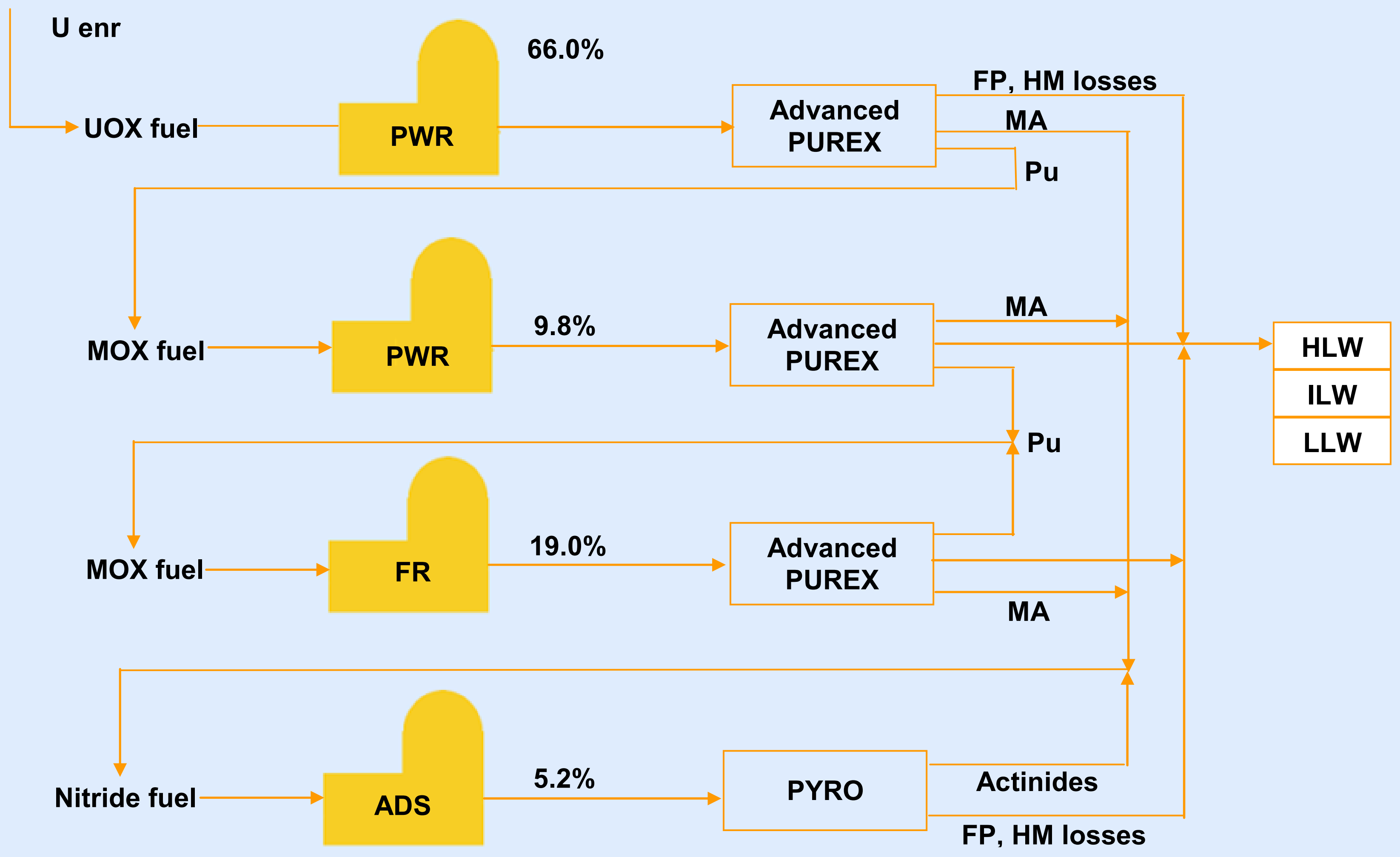
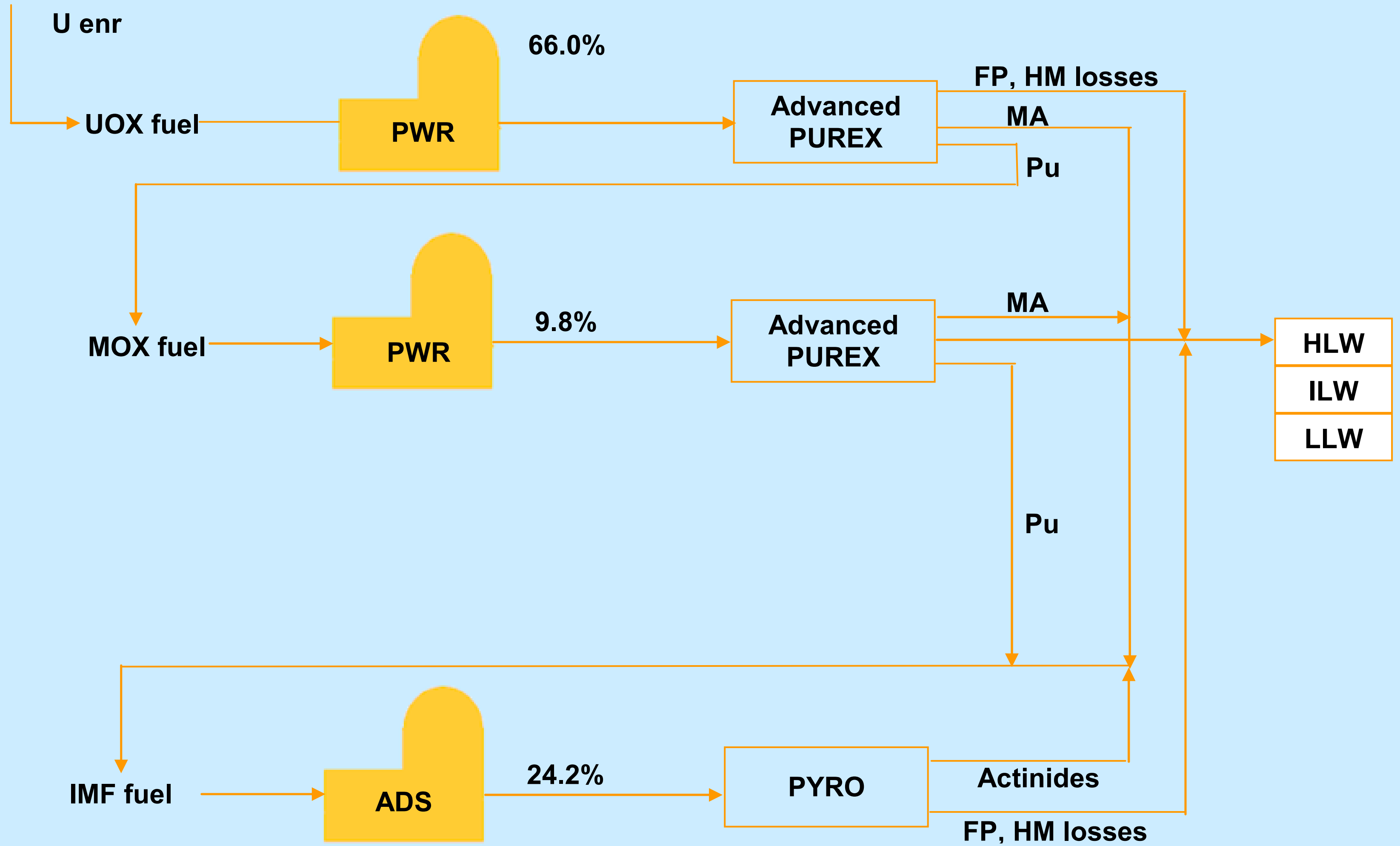
Double strata scheme 3b



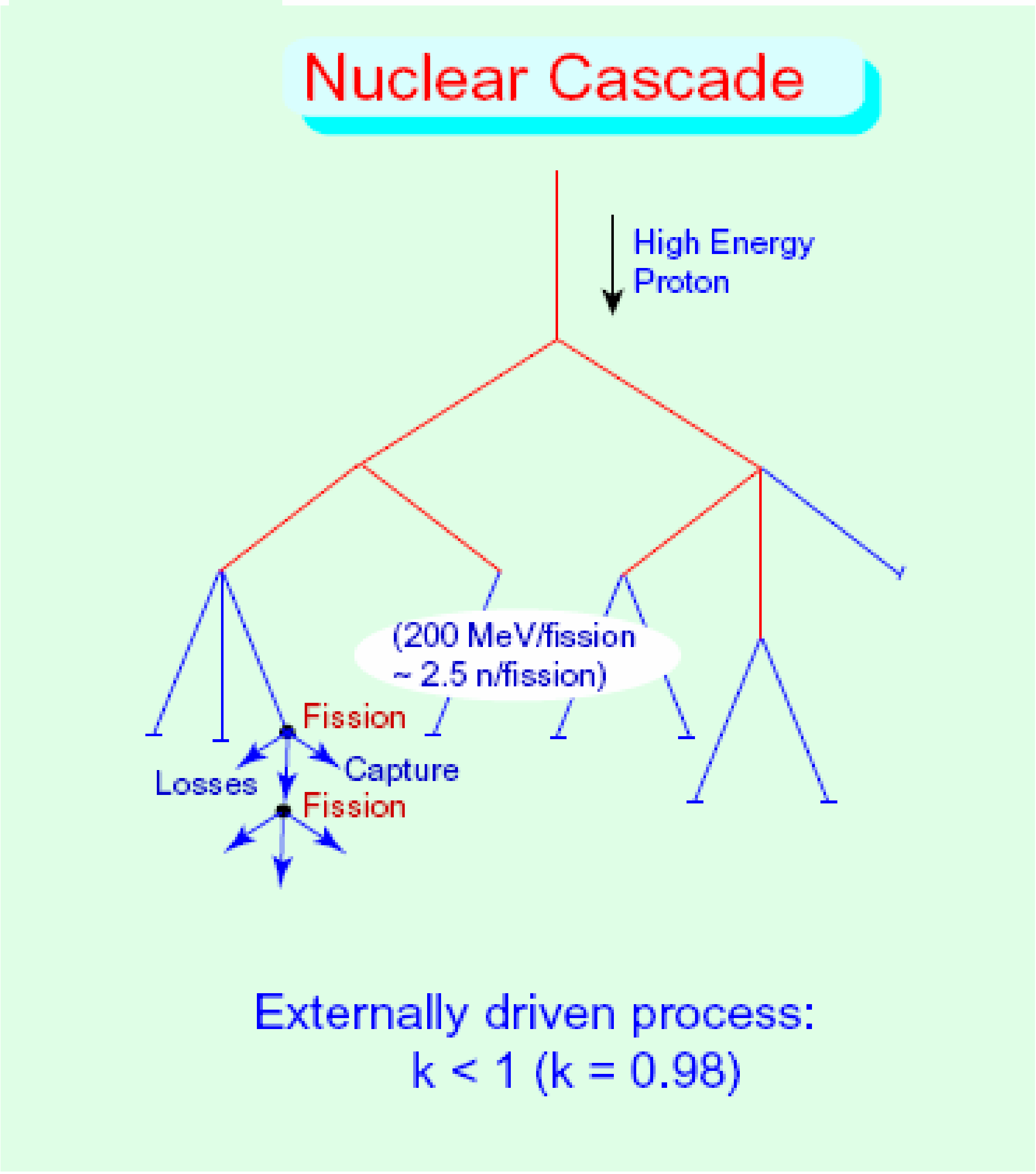
Double strata fuel cycle: burns all plutonium in conventional LWRs and fast reactors.

Fuel cycle schemes

Double strata scheme 3bV (variant)



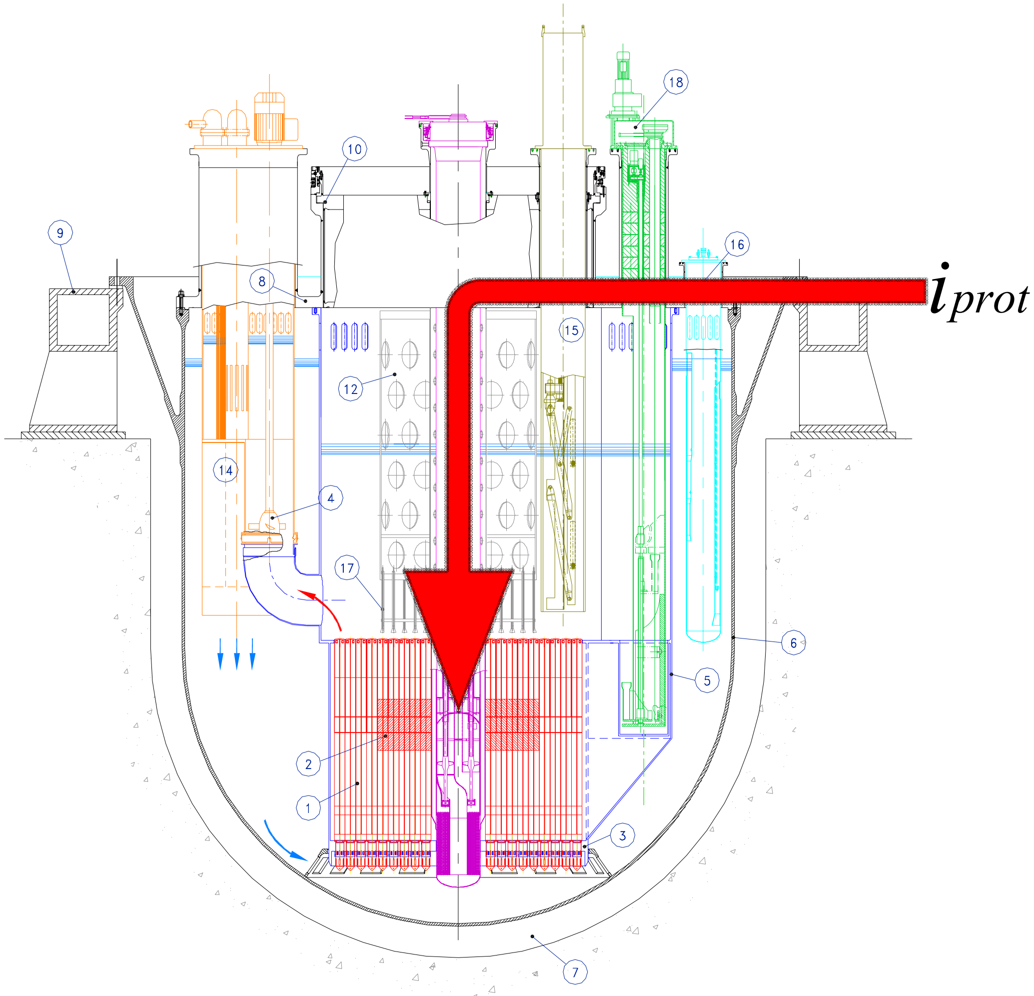
Double strata fuel cycle: Pu is transferred from the PWR-MOX stage directly to the ADS fuel cycle.



Source

Y. Kadi, J.P. Revol

Basic concepts



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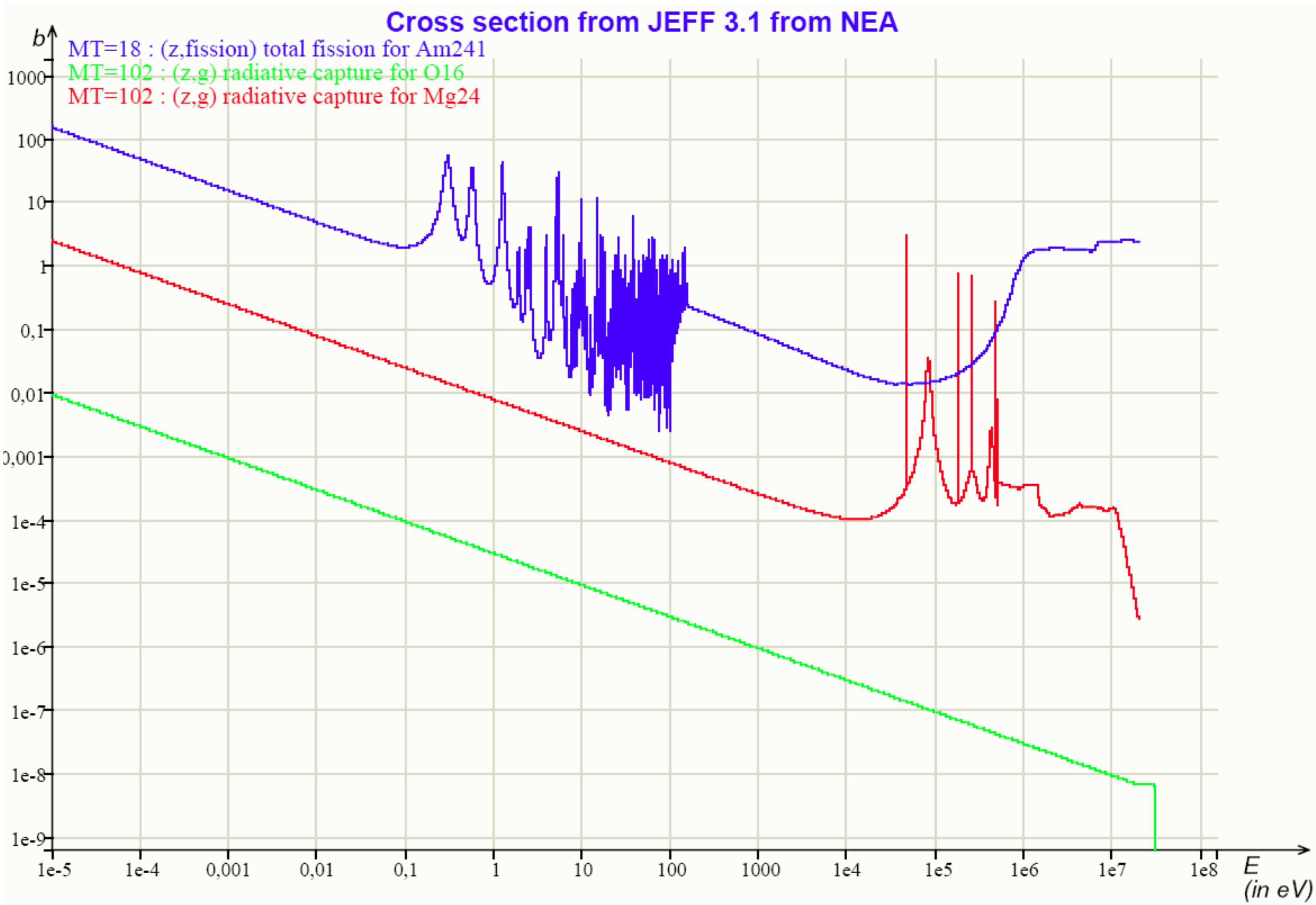
- Inert Matrix Fuel (IMF) is a type of nuclear reactor fuel that consists of a neutron-transparent matrix and a fissile phase that is either dissolved in the matrix or incorporated as macroscopic inclusions.

- The matrix plays a crucial role of diluting the fissile phase to the volumetric concentrations required by reactor control considerations, the same role ^{238}U played in conventional Low Enriched Uranium (LEU) or Mixed OXide (MOX) fuel.

- The key difference is that replacing fertile ^{238}U with a neutron-transparent matrix eliminates plutonium breeding as a result of neutron capture.


Cross section from JEFF 3.1 from NEA
b
MT=18 : (z,fission) total fission for Am241
MT=102 : (z,g) radiative capture for O16
MT=102 : (z,g) radiative capture for Mg24
1000
100
10
1
0,1
0,01
0,001
1e-4
1e-5
1e-6
1e-7
1e-8
1e-9
1e-5
1e-4
0,001
0,01
0,1
1
10
100
1000
1e4
1e5
1e6
1e7
1e8
E
(in eV)

EUROTRANS DM1 Task 1.2.4:
EFIT Core Design

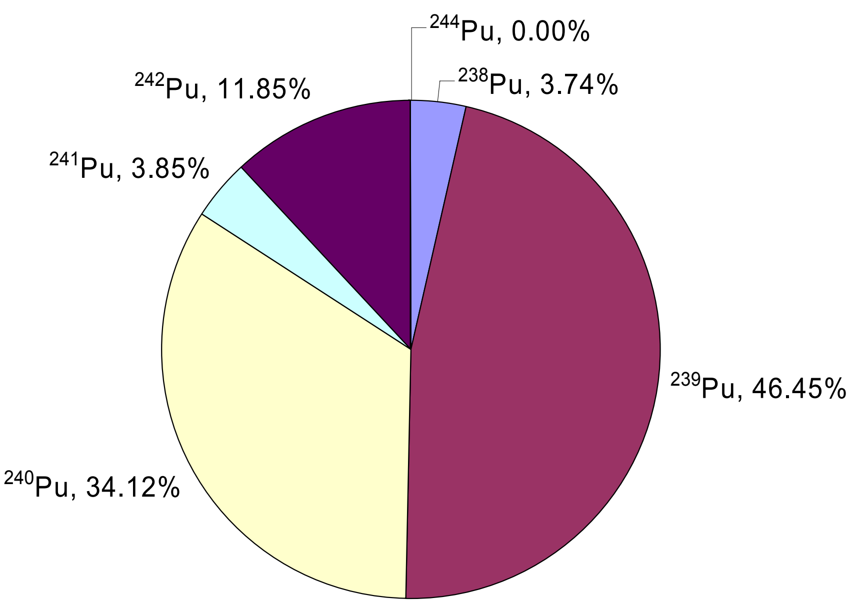
- The **EFIT** (European Feasibility for Industrial Transmutation, VI FP, IP EUROTRANS) concept developed for the transmutation of MAs
- Neutronic design of a **Pb cooled sub-critical core** (ADS with k_{eff} (t) $\leq$ 0,97)

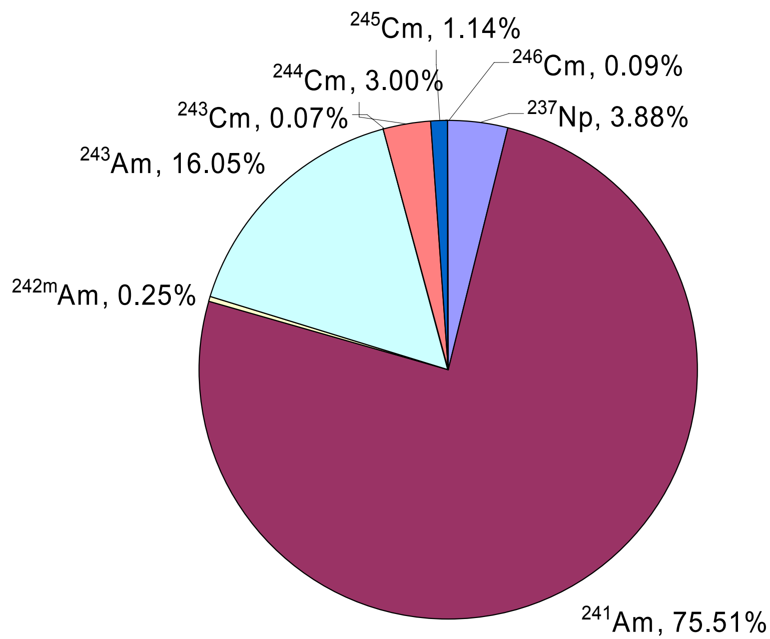
EFIT Pb Main features

Goal:	fissioning MA, while producing energy
Fuel:	MA & Pu Oxide in inert matrix (MgO)
Coolant:	Lead, T_{in}=400 °C, T_{out}=480°C
Power:	several hundreds MW

Project parameters (as inputs)

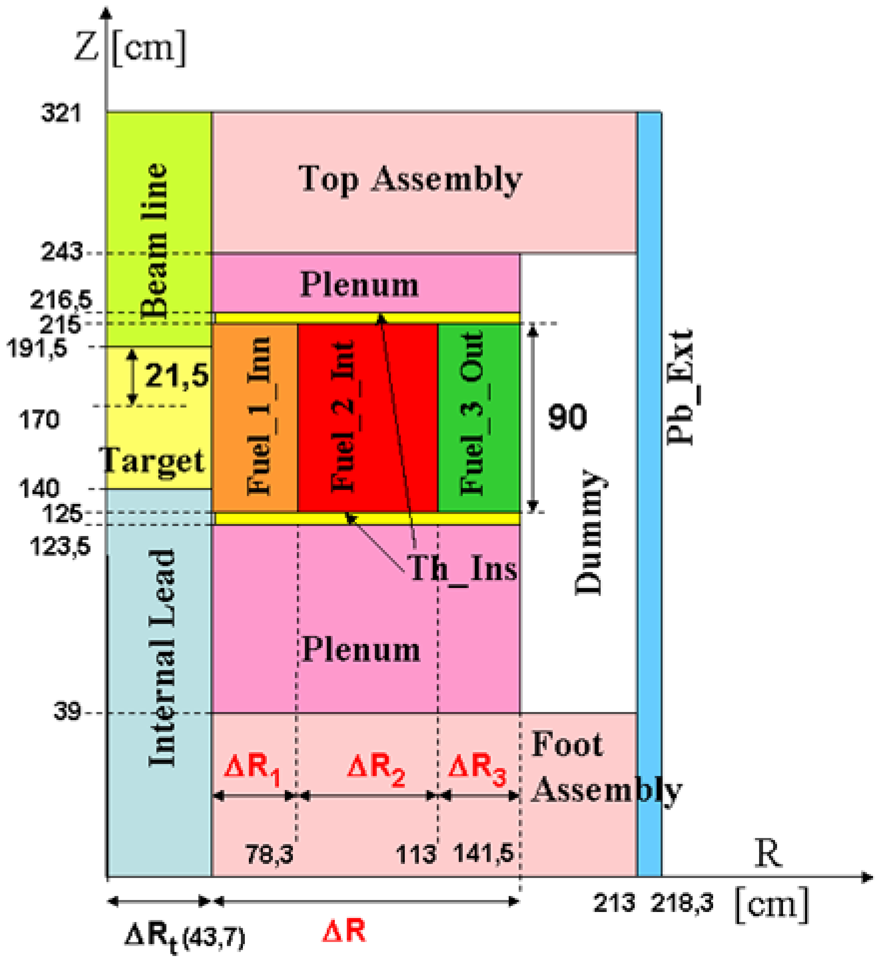
- Thermal power of some hundreds of MW (to be optimized)
- Pb coolant for the proton target and the core (fast spectrum). Pb temp. for the core: T_{in}=673 K, T_{out}=753 K
- External proton beam of 800 MeV up to 20 mA
- Sub-critical level of k_{eff} = 0.97 (to be verified *a posteriori*)
- The fuel is U-free and uses Pu and MA vectors. MA come from the spent UO_2 (90%) and MOX fuel (10%) of a PWR (45 MWd/kgHM) with 30 cooling years. Pu from UO_2 with 15 cooling years (data from CEA).

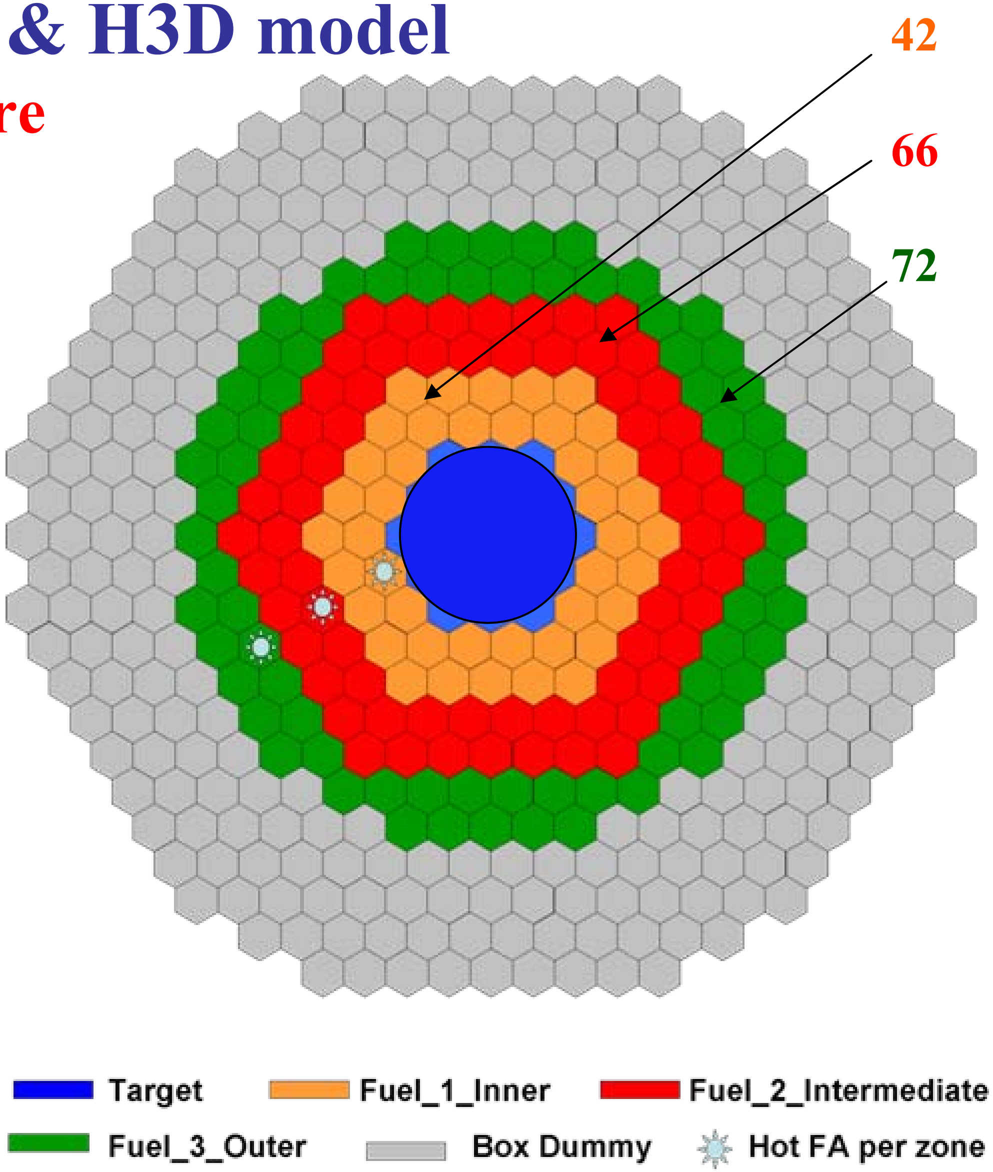


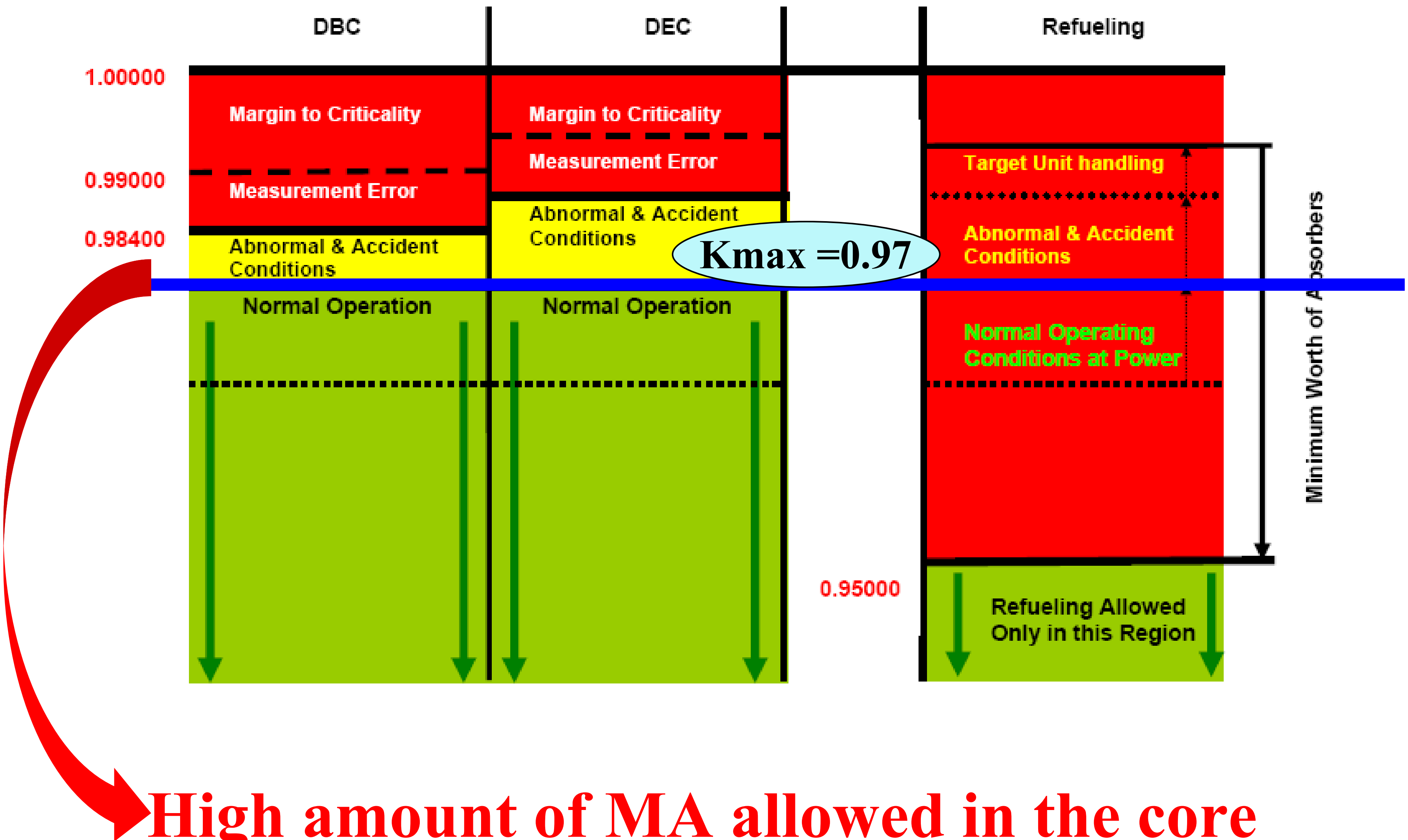


Cylindrised vertical section & H3D model

384 MWth core







High amount of MA allowed in the core

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Main questions to be answered

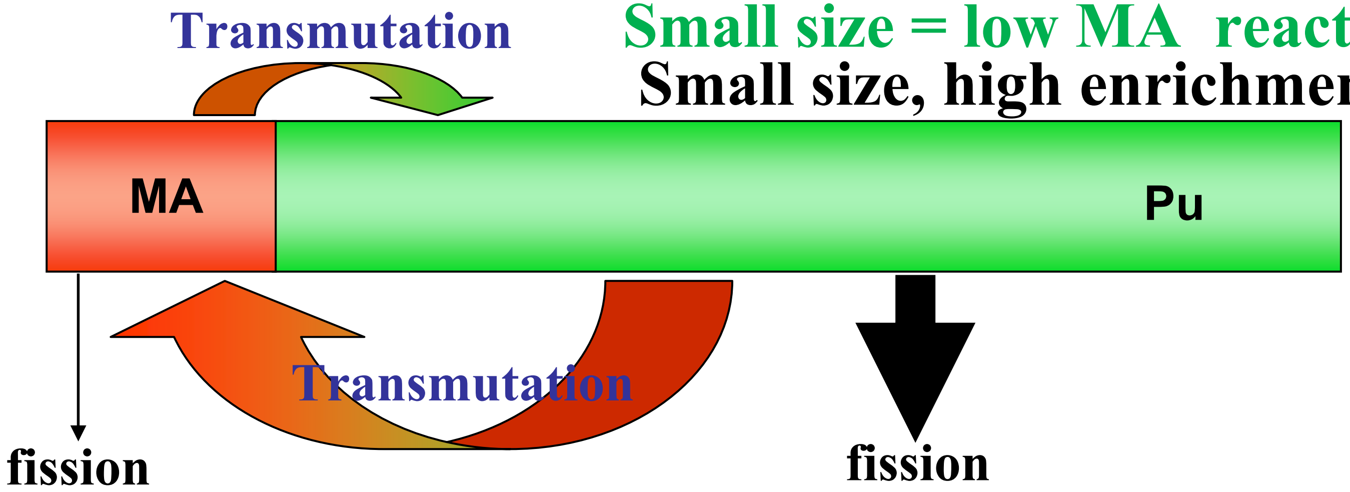
1)What exactly means “burning MA at best” ?

2) In which way the burning capability has to be optimized?

3) What about the two goals: “burner” and “energy producer”?

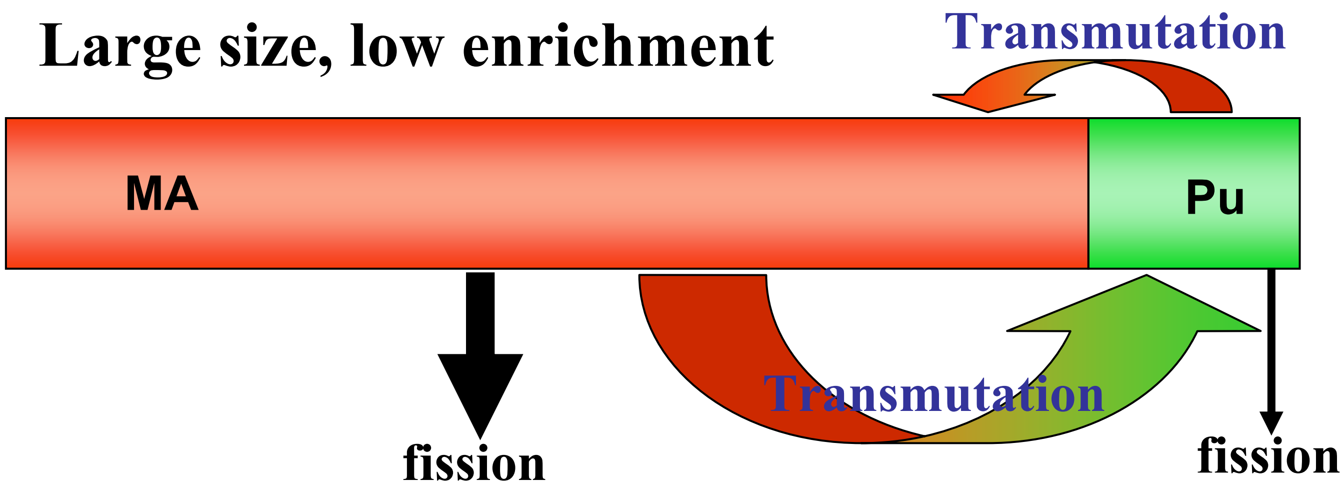
Small size = low MA reaction rate

Small size, high enrichment

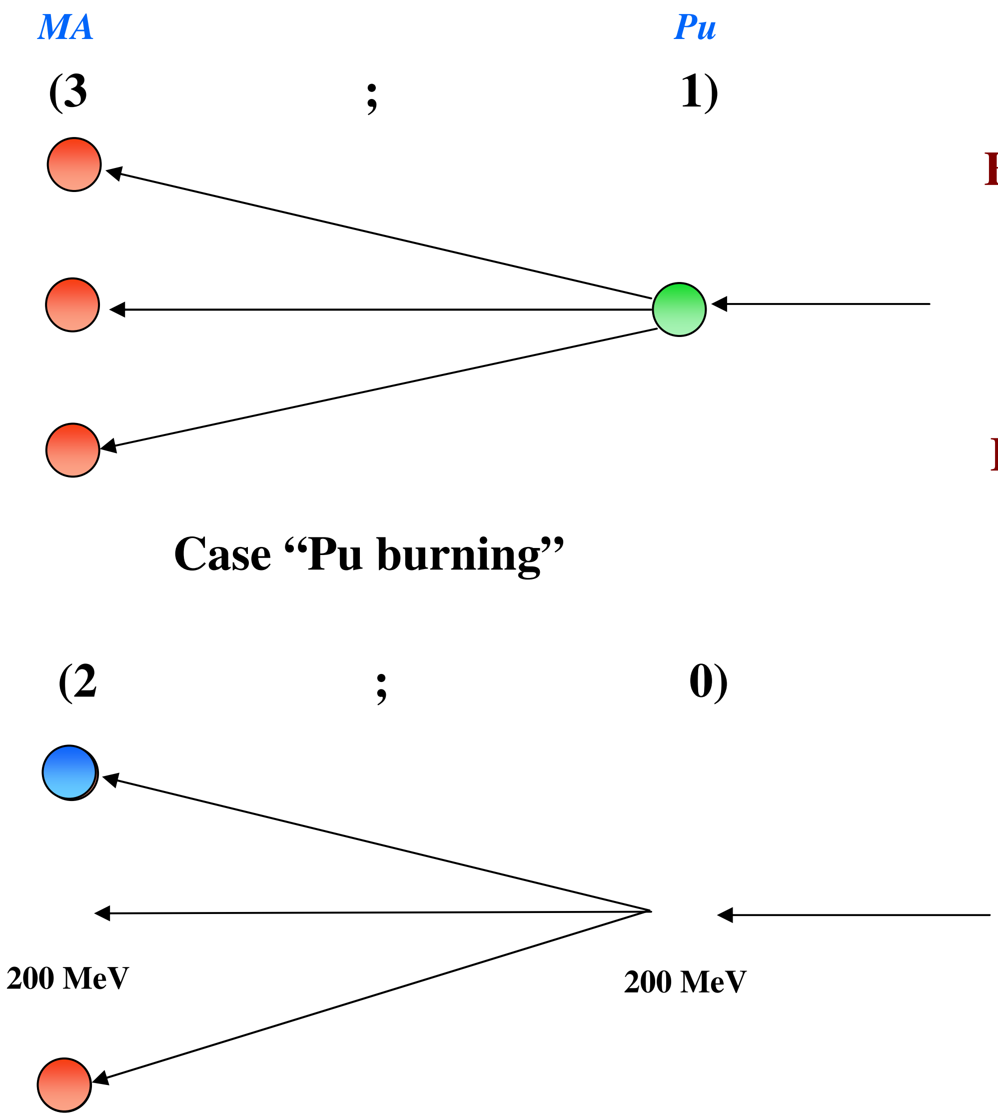


Large size = high MA reaction rate

Large size, low enrichment



The strategy (-42;0)



Balance (at/400 MeV)

(-1 ; -1)

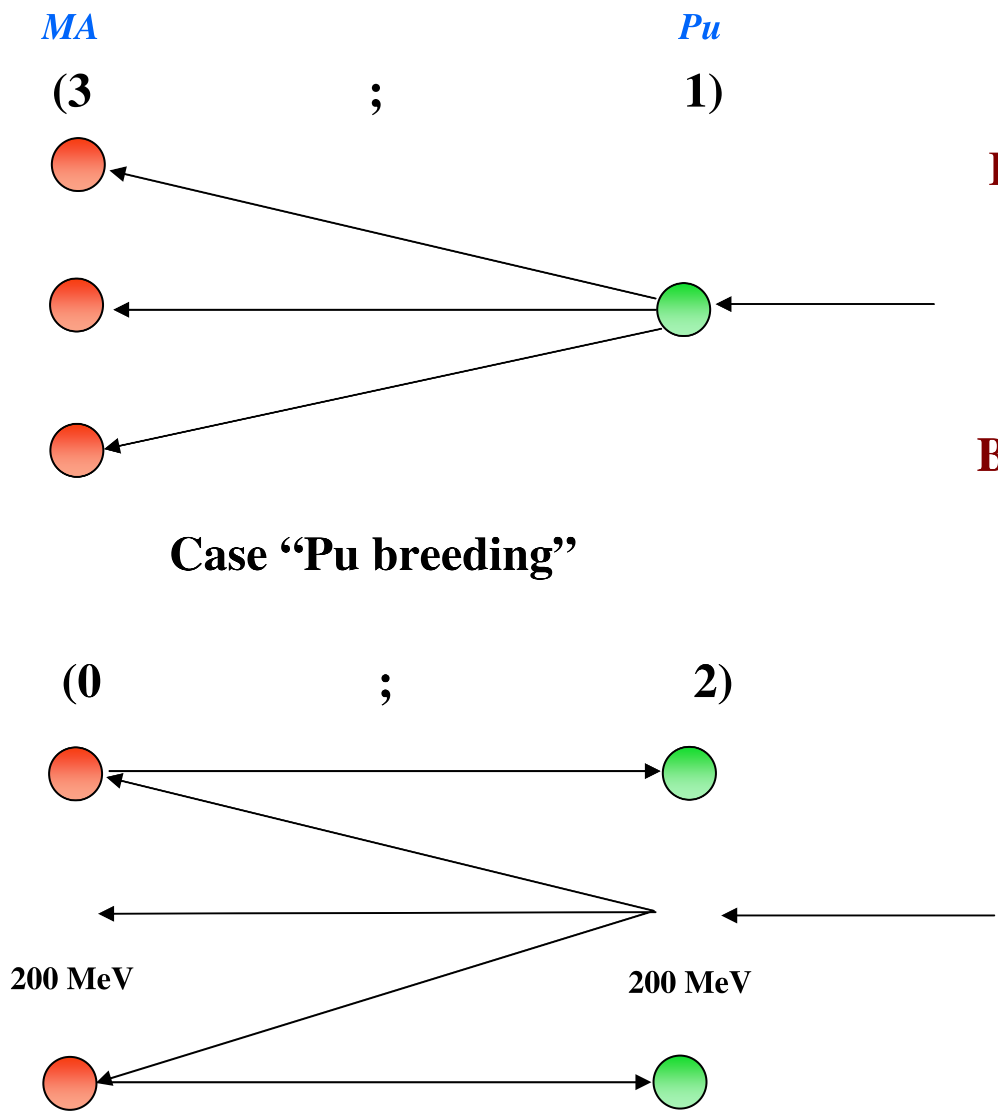
Balance (at/200 MeV)

(-0.5 ; -0.5)

Balance (kg/TWh)

(-21 ; -21)

The strategy (-42;0)



Balance (at/400 MeV)

(-3 ; 1)

↓

Balance (at/200 MeV)

(-1.5 ; 0.5)

↓

Balance (kg/TWh)

(-63 ; 21)

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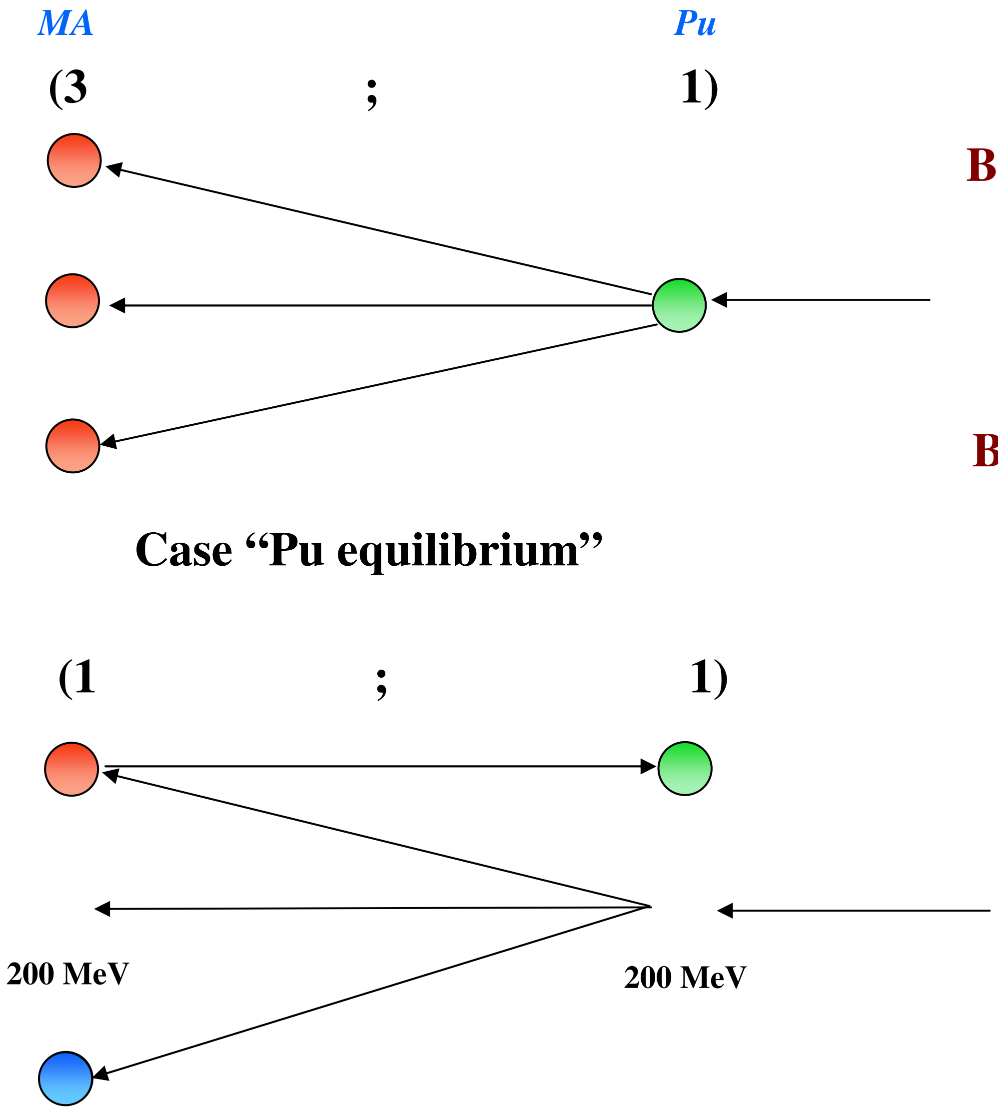
The strategy (-42;0)



Balance (at/400 MeV)

(-2 ; 0)

Balance (at/200 MeV)

(-1 ; 0)

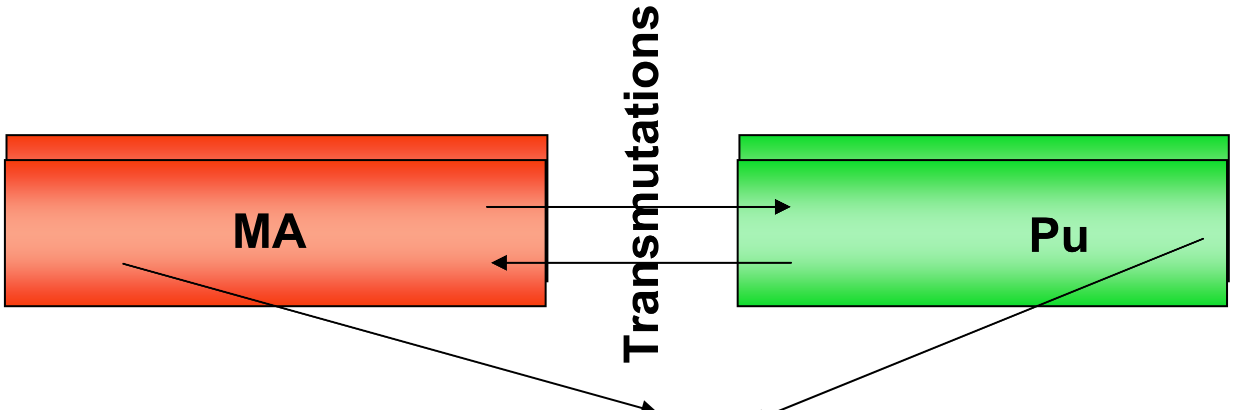
Balance (kg/TWh)

(-42 ; 0)

FUEL

The burning performance depends on the mutual ratio between Pu and MA i.e. on the enrichment

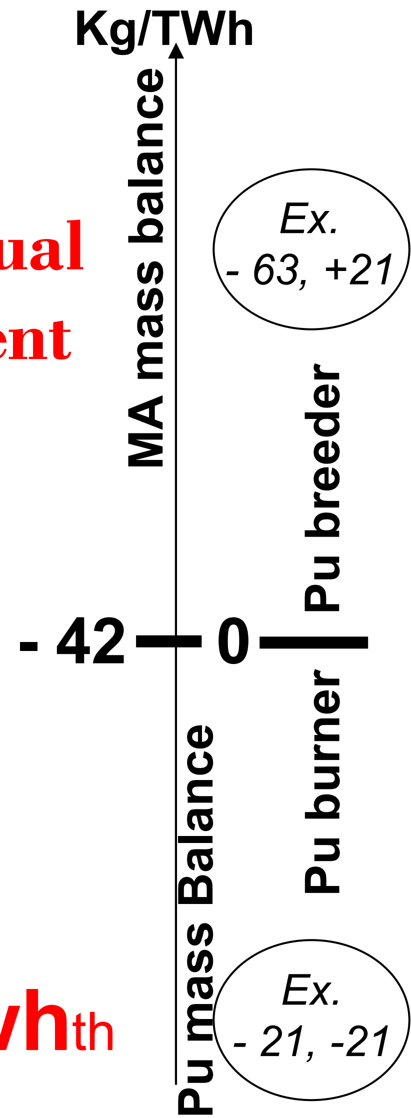
e = Pu / (Pu+ MA)



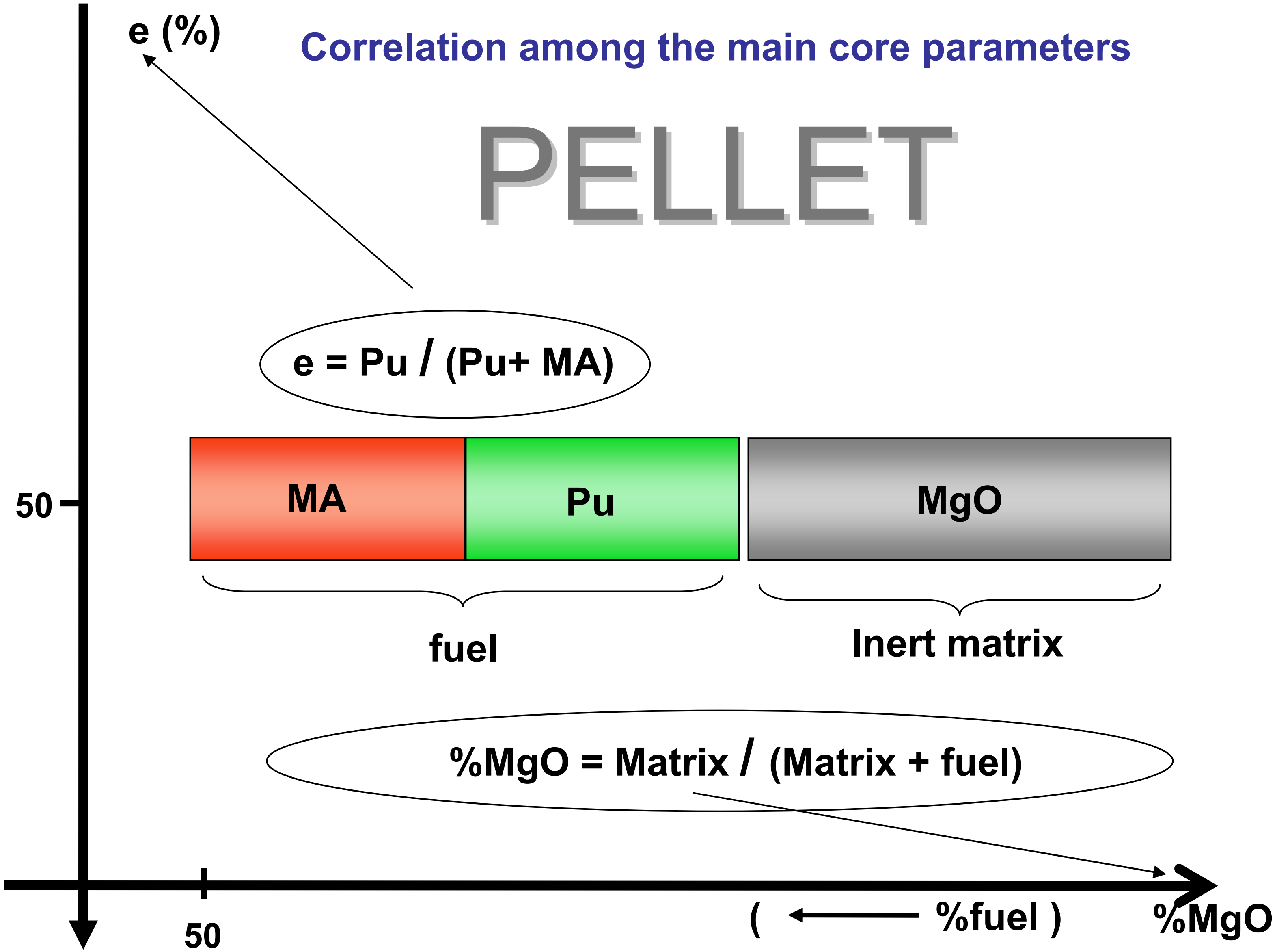
Fission product

Total balance ≈ - 42 kg / Twh$_{th}$

(from theor. 200 MeV/fission)



Correlation among the main core parameters



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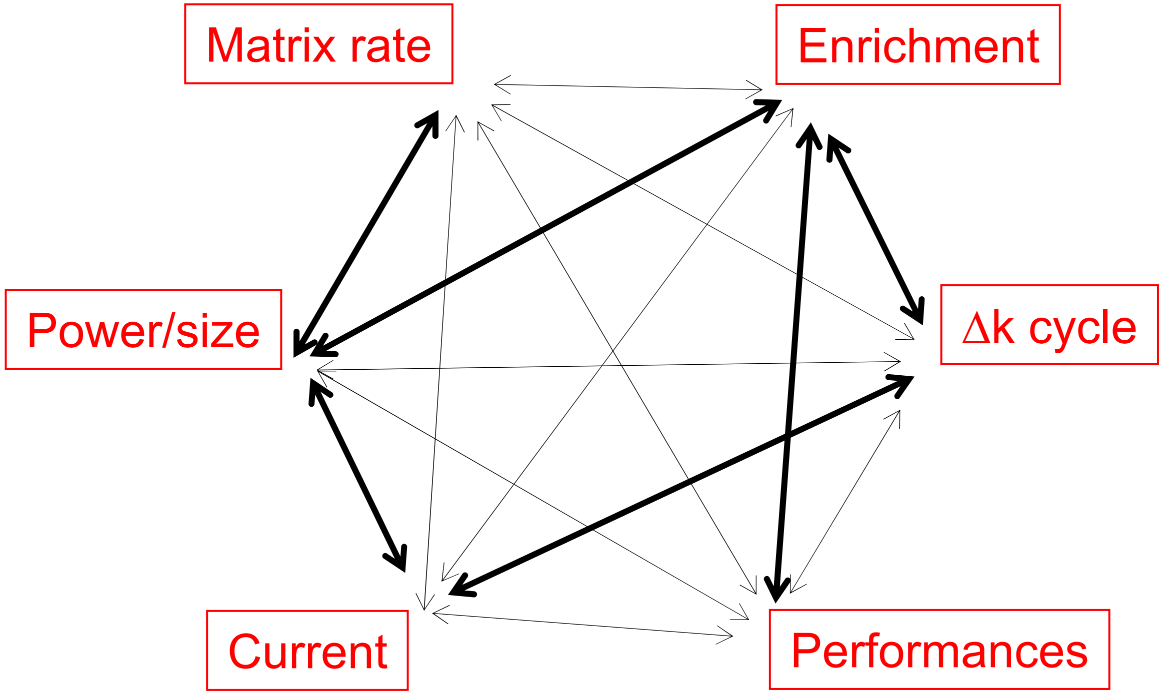
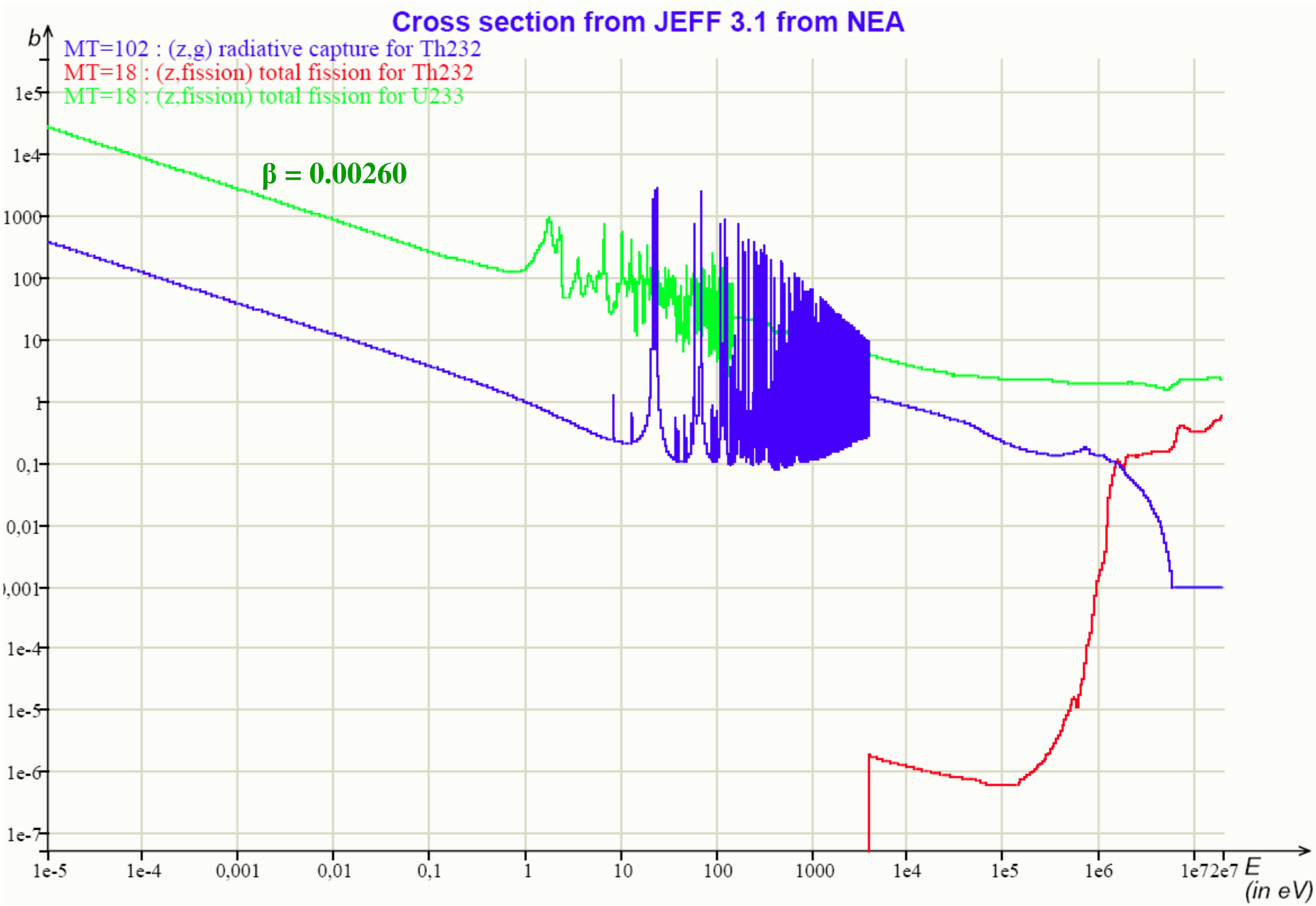
Correlation among the main core parameters



Thorium


Cross section from JEFF 3.1 from NEA
MT=102 : (z,g) radiative capture for Th232
MT=18 : (z,fission) total fission for Th232
MT=18 : (z,fission) total fission for U233
β = 0.00260
b
1e5
1e4
1000
100
10
1
0,1
0,01
0,001
1e-4
1e-5
1e-6
1e-7
1e-5
1e-4
0,001
0,01
0,1
1
10
100
1000
1e4
1e5
1e6
1e7
2e7
E
(in eV)

Conclusions

- ✓ **Advanced fuel cycles offer possibilities for various strategic choices on uranium resources and on optimization of waste repository sites and capacities.**
- ✓ **It is therefore possible to design for acceptable costs innovative nuclear reactor cycles, which at the same time spare resources and make the most efficient use of the foreseen geological repository sites.**
- ✓ **Only transmutation strategies with fully closed fuel cycles can meet the hundredfold TRU reduction goal of P&T. Partially closed fuel cycles, which cannot achieve such high TRU reductions but are easier to implement, are also useful for managing plutonium and minor actinides.**
- ✓ **At the very long-term, i.e. after a few million years, the total dose is somewhat lower in the case of the fully closed fuel cycle scenarios, because much smaller amounts of actinides have to be disposed of in the repository. The activity of the high level waste arising from advanced fuel cycles decreases faster than that of the reference fuel cycle.**