Comparative Study of ADS-burners with Thermal, Intermediate and Fast Neutron Spectrum for Transmutation of Minor Actinides

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~ 90% of radiotoxicity of the spent nuclear fuel is contributed by the transuranium (TRU) elements, i.e. isotopes of plutonium, neptunium, americium and curium

Two schema of atomic power:

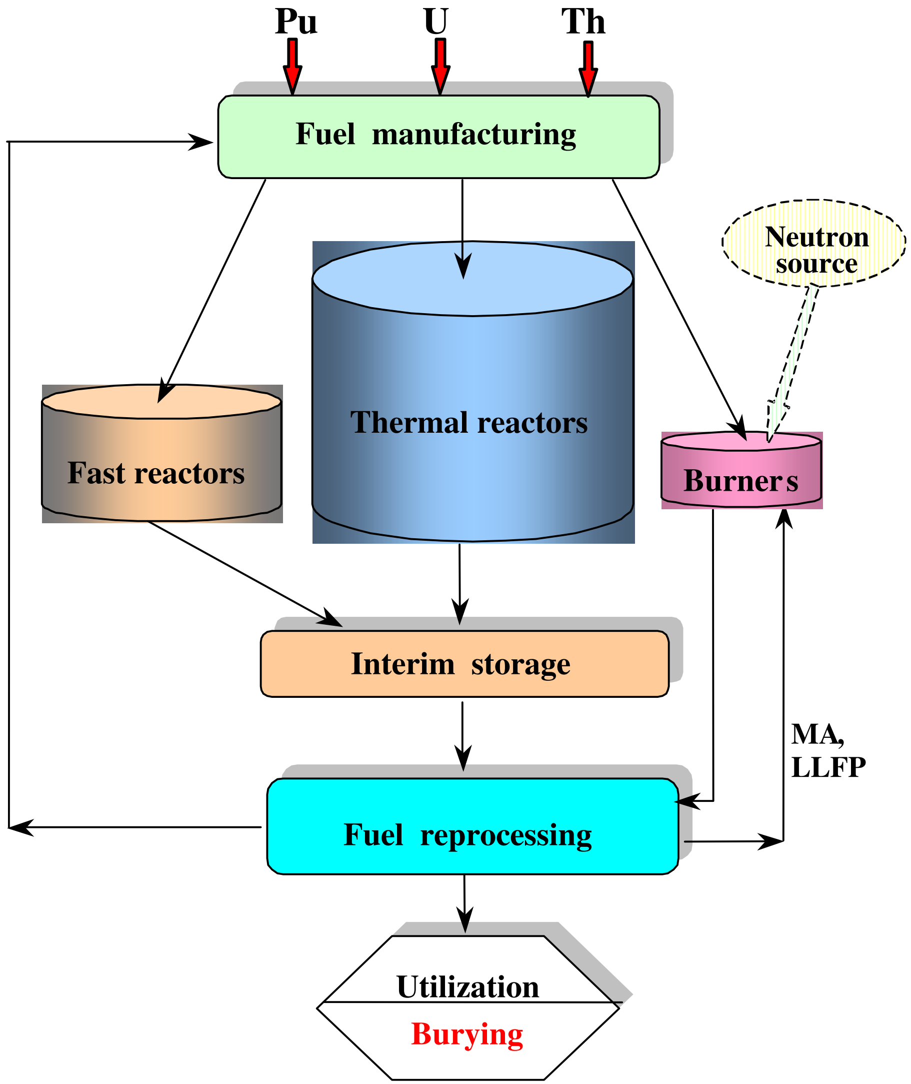
Two component scheme:

- thermal reactors,
- fast reactors.

Three component scheme:

- thermal reactors,
- fast reactors,
- reactor-burners.

How to select the most effective reactor-burner?



Three-component nuclear power system with a closed nuclear fuel cycle

List of the hazard TRU isotopes

^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu

^{237}Np

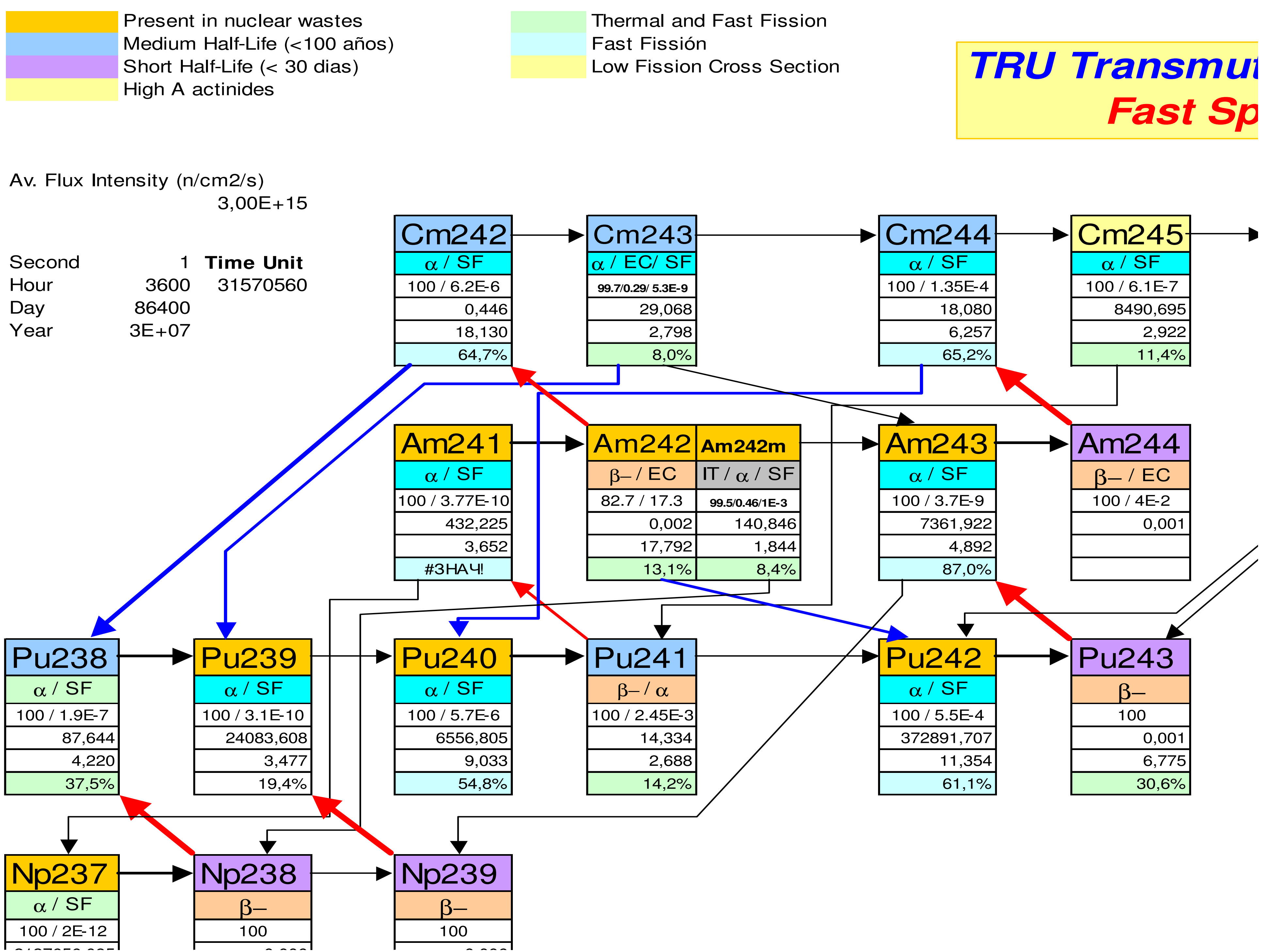
^{241}Am, ^{242m}Am, ^{243}Am

^{243}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm

Transuranium elements content in spent fuel

(Nuclear reactor with power 1 GWel produces ~ 1 tonn of RW per year)

Nuclide	Atomic concentration, %		Mass RW after 30 years storage, *kg/tonn*
	VVER	**PWR** [10]	
Np-237	5.2	5.2	0.87
Pu-238	1.4	1.4	0.24
Pu-239	54.7	51.5	9.27
Pu-240	20.0	23.8	3.41
Pu-241	3.0	7.9	0.51
Pu-242	4.5	4.8	0.80
Am-241	9.9	5.2	1.68
Am-242m	< 0.01	< 0.01	$0.12 \cdot 10^{-2}$
Am-243	0.9	0.9	0.16
Cm-243	< 0.01	0.0	$0.03 \cdot 10^{-2}$
Cm-244	0.1	0.0	$1.6 \cdot 10^{-2}$
Cm-245	0.02	0.0	$0.31 \cdot 10^{-2}$
Cm-246	< 0.01		$0.03 \cdot 10^{-2}$
TOTAL			



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 Transmut
Fast Sp
Av. Flux Intensity (n/cm2/s)
3,00E+15
Second 1
Time Unit
Hour 3600
31570560
Day 86400
Year 3E+07
Cm242
α / SF
100 / 6.2E-6
0,446
18,130
64,7%
Cm243
α / EC/ SF
99.7/0.29/ 5.3E-9
29,068
2,798
8,0%
Cm244
α / SF
100 / 1.35E-4
18,080
6,257
65,2%
Cm245
α / SF
100 / 6.1E-7
8490,695
2,922
11,4%
Am241
α / SF
100 / 3.77E-10
432,225
3,652
#ЗНАЧ!
Am242
β– / EC
82.7 / 17.3
0,002
17,792
13,1%
Am242m
IT / α / SF
99.5/0.46/1E-3
140,846
1,844
8,4%
Am243
α / SF
100 / 3.7E-9
7361,922
4,892
87,0%
Am244
β– / EC
100 / 4E-2
0,001
Pu238
α / SF
100 / 1.9E-7
87,644
4,220
37,5%
Pu239
α / SF
100 / 3.1E-10
24083,608
3,477
19,4%
Pu240
α / SF
100 / 5.7E-6
6556,805
9,033
54,8%
Pu241
β– / α
100 / 2.45E-3
14,334
2,688
14,2%
Pu242
α / SF
100 / 5.5E-4
372891,707
11,354
61,1%
Pu243
β–
100
0,001
6,775
30,6%
Np237
α / SF
100 / 2E-12
Np238
β–
100
Np239
β–
100

Usual criterion of transmutation efficiency:

the transmutation rate q_{MA} [kg/year]

or

number of neutrons per one MA fissioned nucleus.

It depends on the MA fission cross-sections σ_f and the neutron flux Φ of the reactor-burners.

Proposed transmutation efficiency criteria

- transmutation rate q_{MA} [kg/year];
- transmutation time τ [year];
- feeding ratiou $\varepsilon = \text{Pu/MA}$.

In the equilibrium regime the MA transmutation rate $\boldsymbol{q}_{\mathrm{MA}}$ is equal to MA feeding rate.

Feeding ratiou

$$\varepsilon = \mathbf{Pu/MA}$$

is the relative amount of plutonium (or other fissile nuclides) necessary to maintain the given subcriticaly Δk.

Transmutation rate

$$\tau = \tau_{in} + \tau_{out}$$

τ_{in} - is the time of MA irradiation in reactor necessary for the total transmutation of the loaded MA together with all TRU produced by MA and Pu in the transmutation chains.

τ_{out} - is the duration of the outer nuclear fuel cycle (NFC). Today:

$$\tau_{out} / \tau_{in} \approx 3.$$

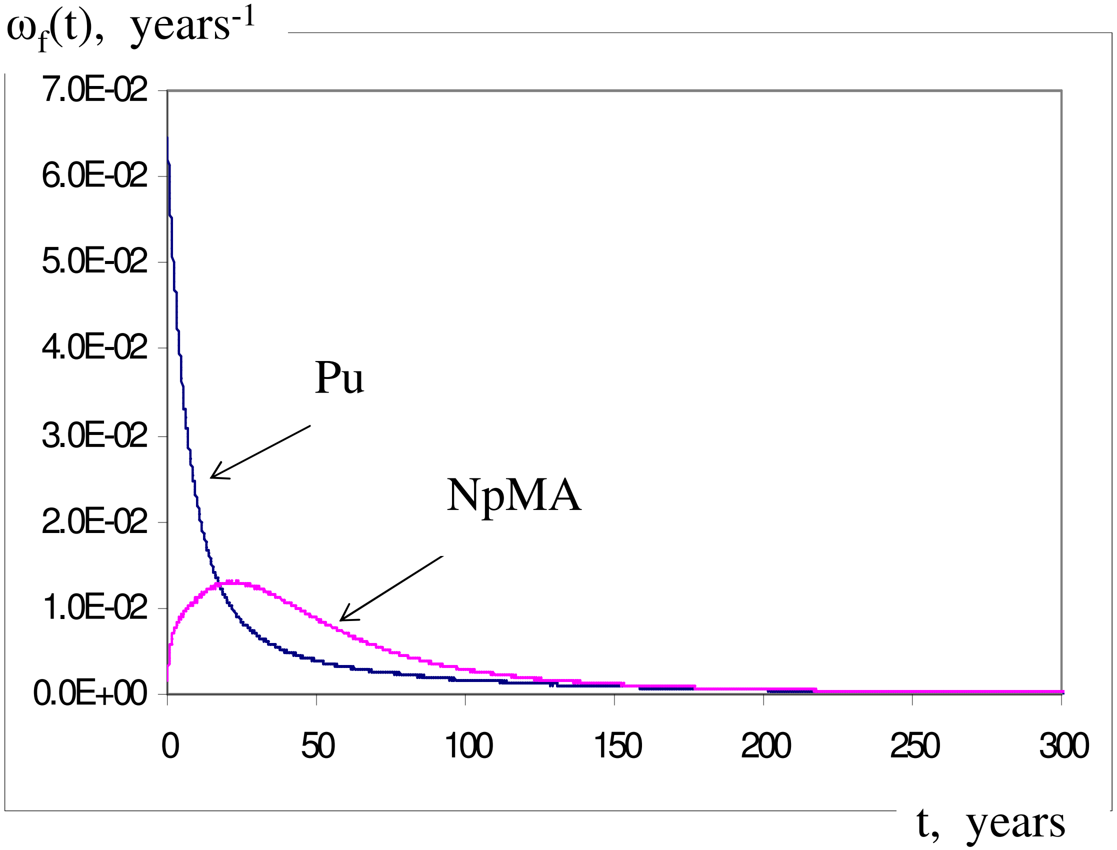
$$\tau_{in} = \int_0^\infty t \cdot \omega_f(t)dt$$

where $\omega_f(t)$ is the probability density of TRU fission.

In the equilibrium regime

$$G_{TRU}^{in} = q_{MA} \int_0^\infty [1 - \int_0^t \omega_f(t')]dt' \xrightarrow[t \to \infty]{} q_{MA} \cdot \tau_{in}$$

$$\tau_{in} = G_{TRU}^{in} / q_{MA}$$



$$\tau_{in}^{Pu} = 46\ years$$

$$\tau_{in}^{MA} = 67\ years$$

ADS chosen for comparison

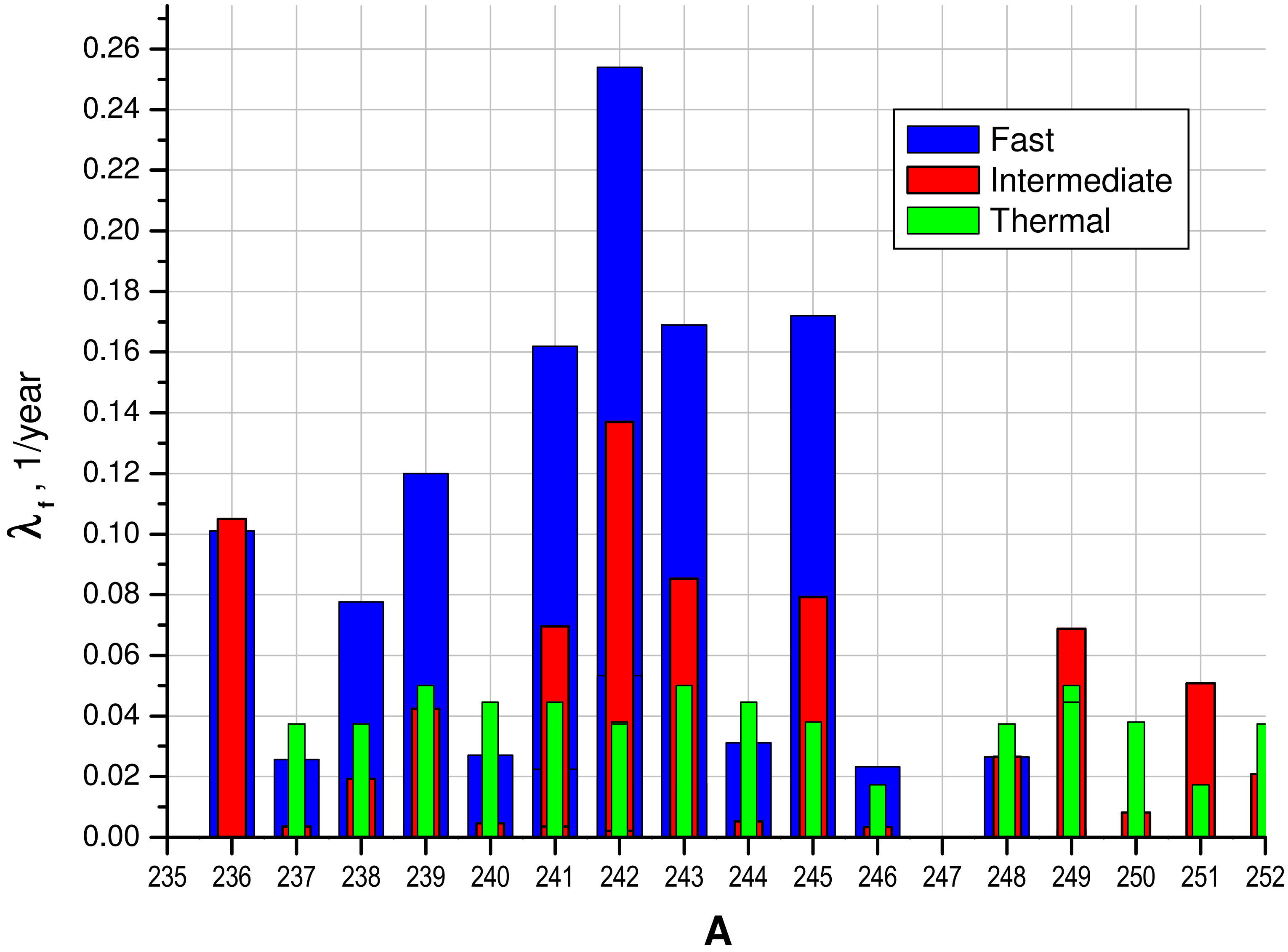
- Heavy water reactor (thermal spectrum);
- Molten salt reactor (intermediate spectrum);
- Lead-bismuth reactor (fast spectrum).

Proton accelerator-driver:

power – 10 MW;

energy – 1 GeV;

current –10 mA.



Fast
Intermediate
Thermal
λf , 1/year
A
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252

Characteristics of chosen ADS-burners at Keff=0.95

(accelerator power W_a = 10 MW, E_a = 1 GeV, I_a = 10 mA)

Reactor characteristics	**Neutron spectrum**		
	Fast	*Intermediate*	*Thermal*
Subcriticality Δk	0.05	0.05	0.05
ADS power, *MW*	330	760	300
Neutron flux Φ, $n/cm^2 \cdot s$	$1.5 \cdot 10^{15}$	$4 \cdot 10^{14}$	$4 \cdot 10^{13}$
Pu/MA loading in the equilibrium cycle, *tonn*	1.1/1.3	10.8/2.7	0.9/0.5
Pu/MA feeding content ε	0.01	2.9	2.5
MA transmutation rate q_{MA}, *kg/year*	120	55	25
Transmutation time τ_{in}, *years*	~20	~205	~ 55
Transmutation time of 1 tonn of TRU τ_{in}/G_{TRU}^{in}, *years/tonn*	~15	~75	~110

Characteristics of chosen ADS-burners at Keff=0.97

Reactor characteristics	Neutron spectrum		
	Fast	*Intermediate*	*Thermal*
Subcriticality Δk	0.03	0.03	0.03
Accelerator power, *MW*	6.0	5.9	10.0
ADS power, *MW*	330	760	500
Neutron flux Φ, $n/cm^2 \cdot s$	$1.3 \cdot 10^{15}$	$4 \cdot 10^{14}$	$3 \cdot 10^{13}$
Pu/MA loading in the equilibrium cycle, *tonn*	1,5/1,9	12.0/2.9	1.5/0.9
Pu/MA feeding content ε	0,01	2.9	3.0
Ttransmutation MA rate q_{MA}, *kg/year*	120	55	40
Transmutation time τ_{in}, *years*	~30	~220	~60
Transmutation time of 1 tonn of TRU τ_{in}/G^{in}_{TRU}, *years/tonn*	~15	~70	~70

TRU Loses

The duration τ_c of the single transmutation cycle

$$\tau_c = \tau_c^{in} + \tau_c^{out}$$

Because $\tau_c << \tau$ it is necessary several reprocessing cycles to transmute the TRU mass G_{TRU}^{in}

$$\mathbf{n_{rep}} = \tau / \tau_c$$

Reprocessing losses:

$$\mathbf{Q = \chi_{loss} \cdot n_{rep}},$$

χ_{loss} is the loss of MA during one reprocessing cycle.
At $\mathbf{n_{rep}}$ ~ 10 and $\mathbf{Q} < 10^{-3}$ it is necessary to have $\chi_{loss} < 10^{-4}$.
Such a level of losses is discussed now in MSR-technology only.

CONCLUSION

Our consideration shows that ADS with LBE blanket is evidently more effective from the point of view τ_{in} and ε :

$$\tau_{in} \sim 15 \text{ years},$$

$$\varepsilon \sim 0.01.$$

Molten salt ADS has preferences in the reprocessing:

$$\tau \sim \tau_{in} .$$

For the final conclusion it is necessary to compare the efficiency of the critical reactor-burners (thermal and fast), taking into account their outer NFC.