SYNERGY OF FISSION AND FUSION: THE PATH TO CLEAN NUCLEAR ENERGY SYSTEM

Technical Meeting
on Synergies Between Nuclear Fusion Technology Developments
and Advanced Nuclear Fission Technologies
06-10, June 2022

Vladimir ARTISYUK

Recommendation of Standing Advisory Group on Nuclear Energy on the Synergies of Fission and Fusion Technologies

ROSATOM

SAGNE supports the initiative of the Agency to implement new activities, including cross-cutting ones, focused on engineering, technology and science, including addressing synergies in technology development between nuclear fission and nuclear fusion as well as fission-fusion hybrid systems for power production and radwaste transmutation.

Contents

- Goals of nuclear waste transmutation
- Fission-fusion harmonization: methodology of measuring
- Specifics of fusion induced transmutation environments

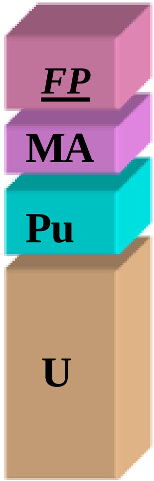
“Evidence on the potential substantial contribution of nuclear energy to climate mitigation objectives was extensive and clear”

“regarding the long-term management of High-Level Waste (HLW), there is an international consensus that a safe, long-term technical solution is needed to solve the present unsustainable situation. A combination of temporary storage plus permanent disposal in geological formation is the most promising…Yet nowhere in the world has a viable, safe and long-term underground repository been established”

“The TEG has therefore not recommended the inclusion of nuclear energy in the Taxonomy at this stage”

Characteristics of hazard from radioanuclides

ROSATOM



Mass (g)

m_i

Source term

Activity (Bq)
Nuclear properties
added

$$A_i = m_i \times \frac{\lambda_i N_{Av}}{Mol_i} = m_i \times \gamma_i$$

Toxicity (ALI)*
Properties of dose absorption
in the human body
added

Potential hazard

$$T_i = A_i \times \frac{1}{ALI_i} = m_i \times \frac{\lambda_i N_{Av}}{Mol_i} \times \frac{1}{ALI_i} = m_i \times \alpha_i$$

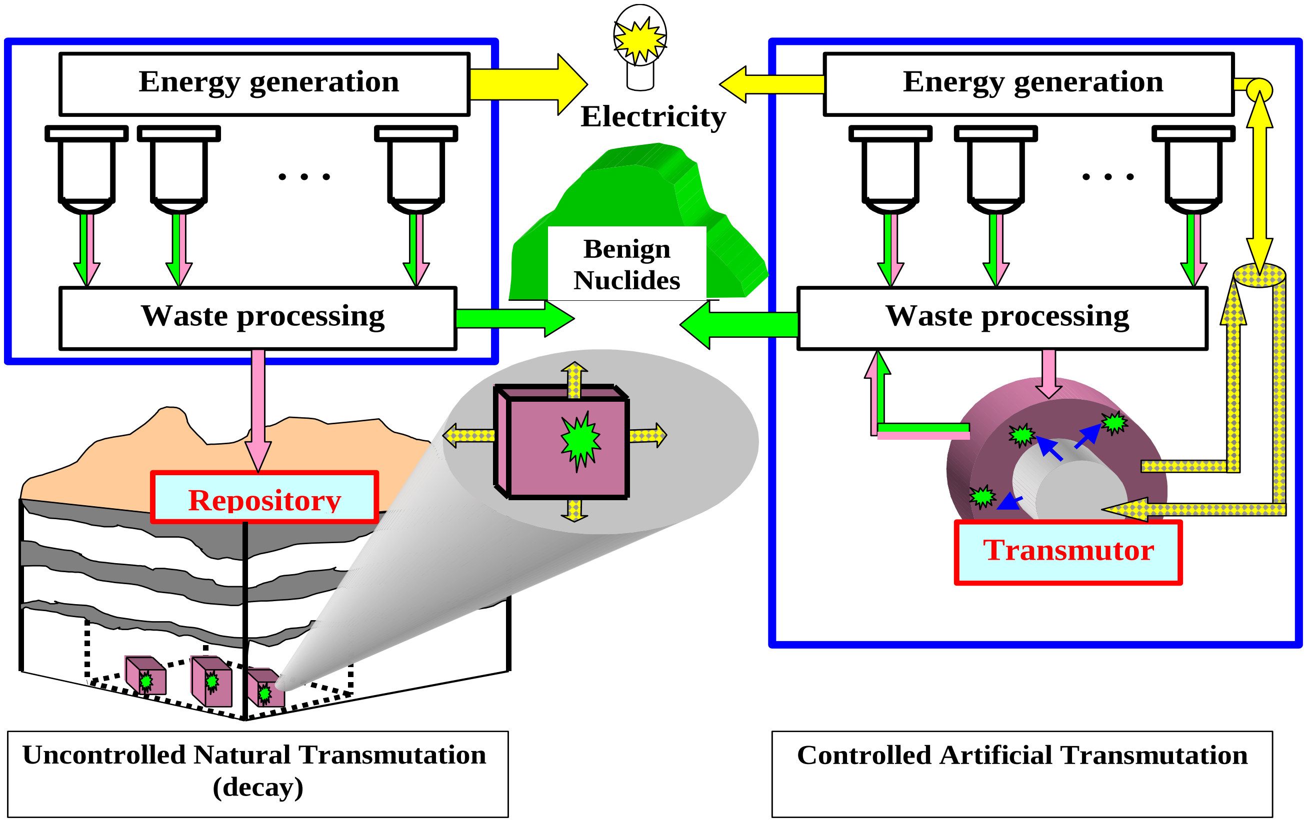
Radiological risk
(rem/m^3)
Properties of retention in geological strata
added

Radiological risk

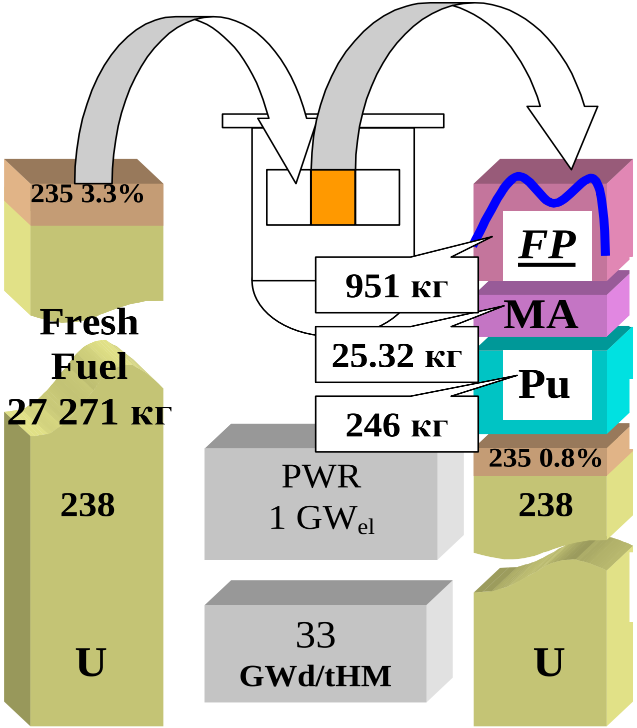
$$R_i = T_i \times f\left(\lambda_i, F_i, K_i, DD_i, t_i\right)$$

***Annual Limit on Intake (ALI)** - is the annual intake of a given radionuclide by "Reference Man" which would result in either a committed effective dose equivalent of **5 rems** (stochastic ALI) or a committed dose equivalent of **50 rems** to an organ or tissue (non-stochastic ALI)

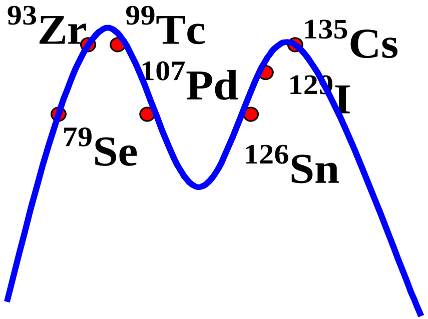
Waste Management Options in a Nutshell



Glance at Nuclear Wastes



Fission Products $T_{1/2} > 10^4$ лет :



MA-recycle → **Energy production (&protection of recycled Pu)**

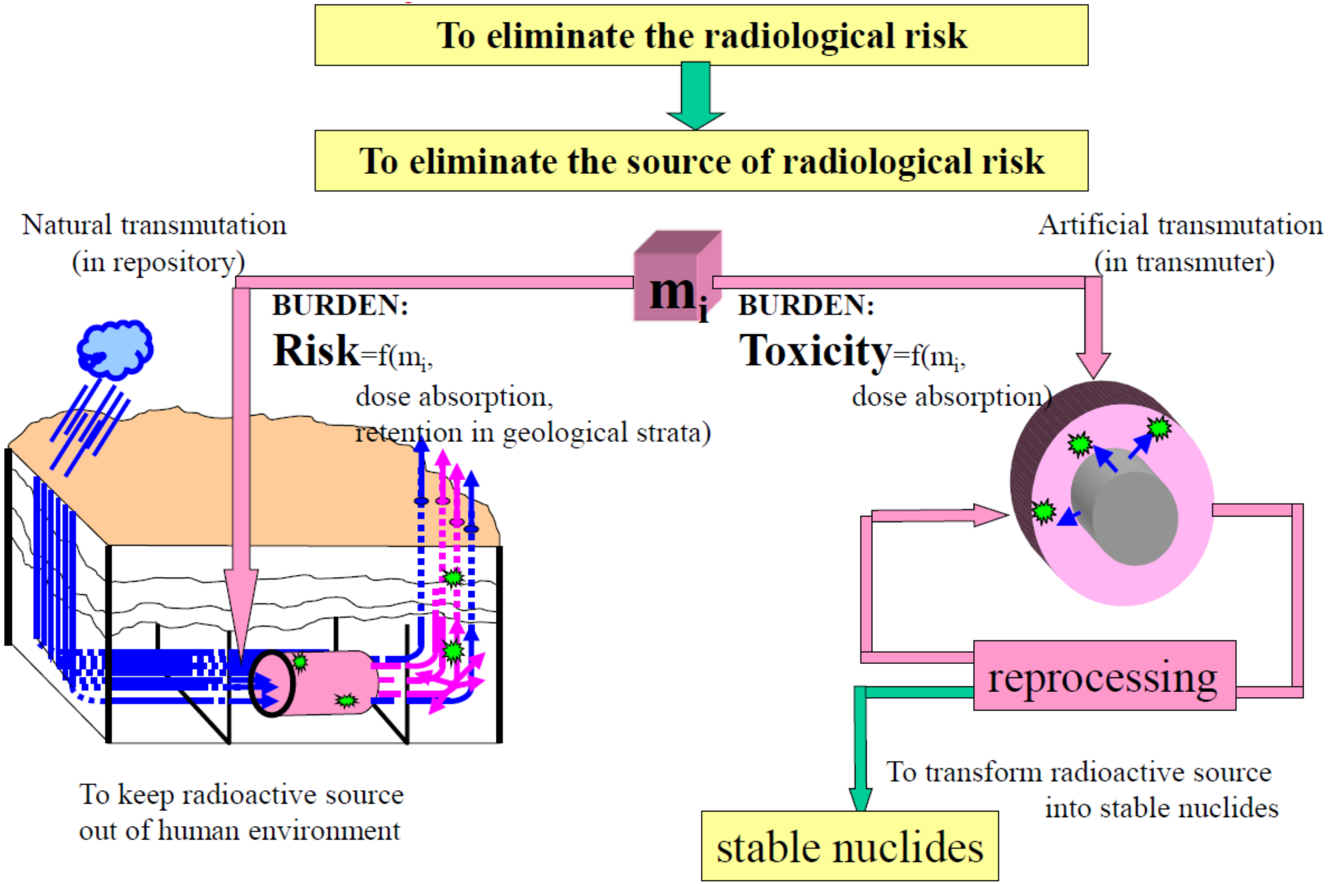
^{237}Np: (n,γ)^{238}Np→ ^{238}Pu

^{241}Am: (n,γ)^{242}Am→^{242}Cm→ ^{238}Pu

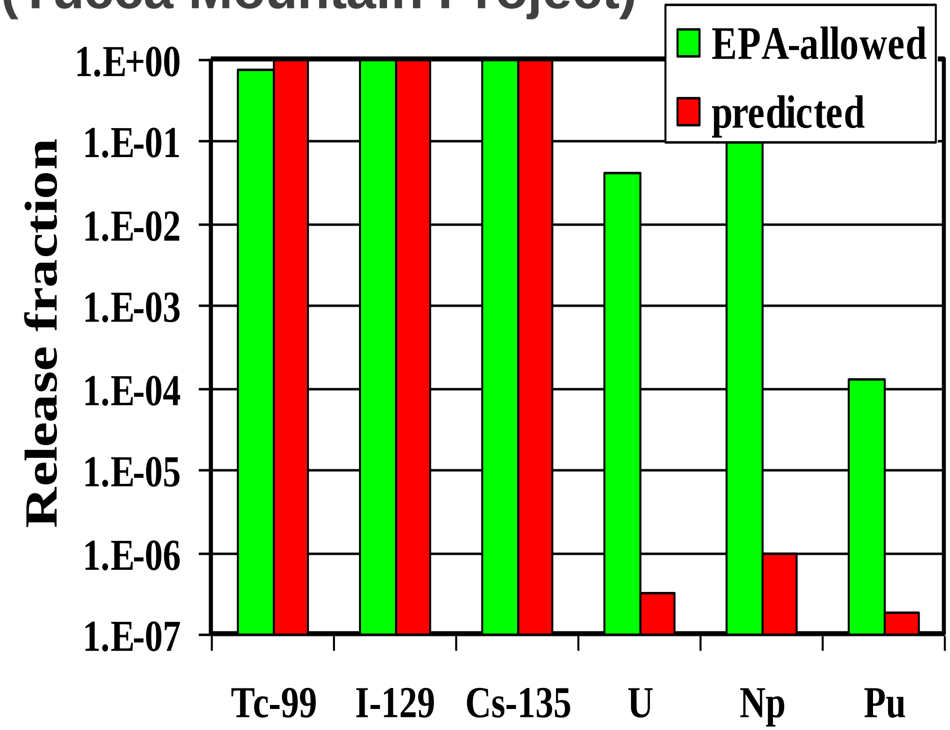
Pu - recycle → **Energy production (&complete use of uranium)**

U - recyle → **Energy production (&uranium saving)**

Objectives of Waste Transmutation



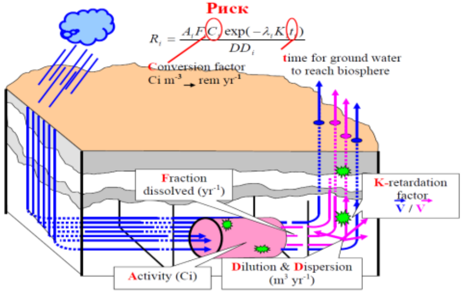
Cumulative Release SNF in 10,000 (Yucca Mountain Project)



EPA - Environmental Protection Agency

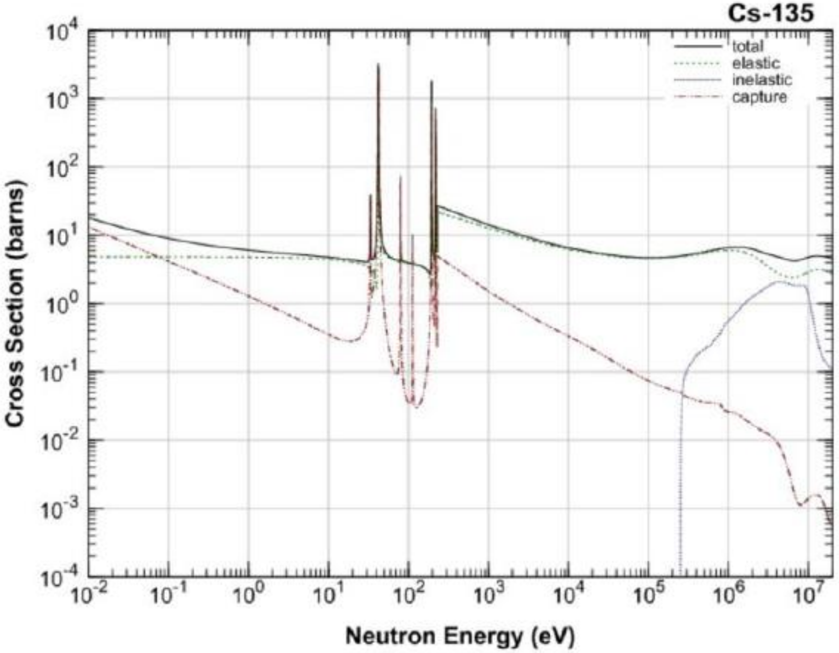
Standards on cumulative yields are taken from:

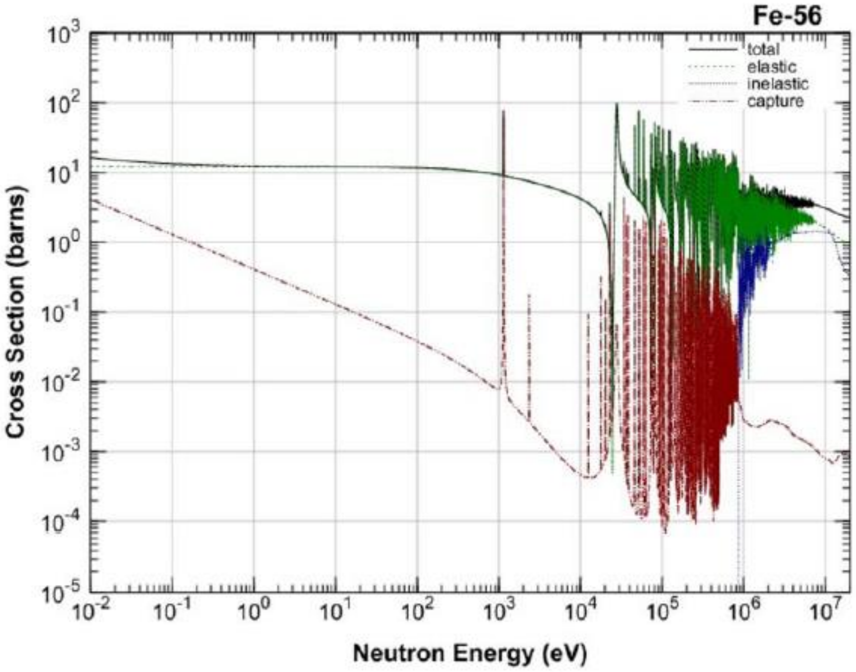
The Code of Federal Regulations, Title 40, Part 191- Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes



* T.PIGFORD, Actinide Burning and Waste Disposal, *Proc. Int. Conf. Next Generation of Nuclear Power Technology*, Berkley, University of California, 5 October, UCB-NE-4176 (1990)

Glance at nuclear properties (the case of Cs-135)



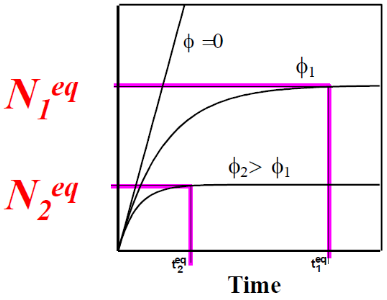


Goals of Waste Transmutation

$$\frac{dN_i}{dt} = Y_i - (\lambda + \sigma\phi)_i N_i \Rightarrow N_i^{eq} = \frac{Y_i}{(\lambda + \sigma\phi)}$$

Characteristics of Transmutation Efficiency

- **Equilibrium Mass**
- **Time to approach equilibrium**



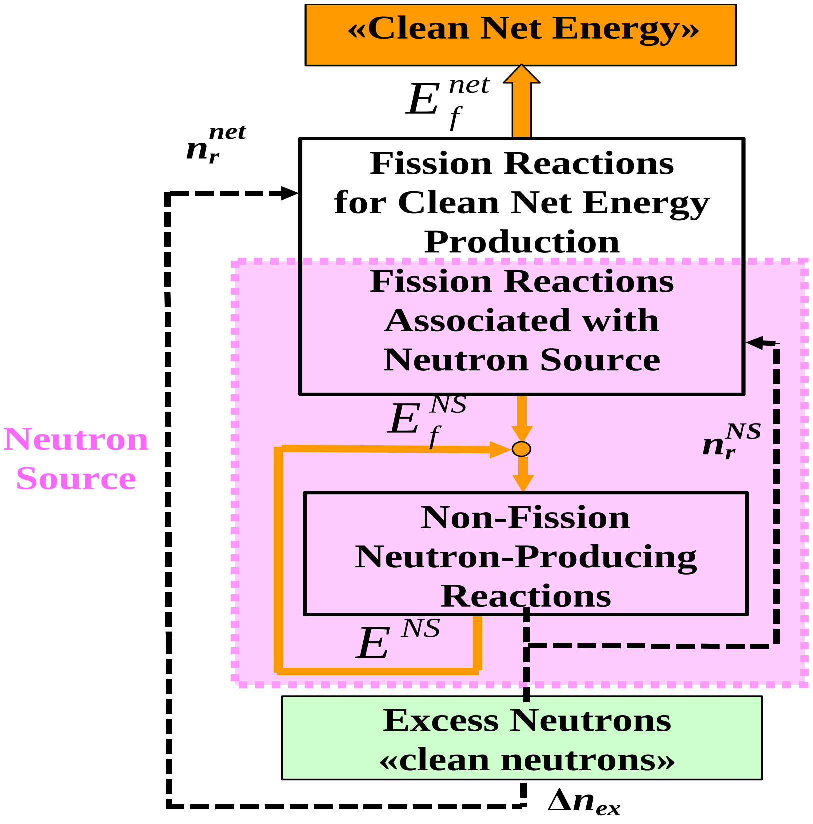
Nuclide	Half-life (yr)	Effective half-life (yr)		Time to approach equilibrium (yr)**	
		Fast Spectrum*	Thermal Spectrum*	Fast Spectrum	Thermal Spectrum
^{79}Se	6.5×10^4	7.3×10^2	2.1×10^3	2.41×10^3	7.07×10^3
^{90}Sr	**29**	**29**	**29**	**≈100**	**≈100**
^{93}Zr	1.5×10^6	730	790	2.44×10^3	2.61×10^3
^{99}Tc	2.1×10^5	110	51	365	170
^{107}Pd	6.5×10^6	44	733	146	2.44×10^3
^{126}Sn	1.0×10^5	4.2×10^3	4.2×10^3	1.4×10^4	1.4×10^4
^{129}I	1.6×10^7	157	51.2	522	170
^{135}Cs	2.3×10^6	310	170	1.04×10^3	562
^{137}Cs	**30**	**30**	**30**	**≈100**	**≈100**

*) thermal spectrum: average energy -1eV, neutron flux- 10^{14} n/(cm^2· s);
fast spectrum: average energy -200 KeV, neutron flux - 10^{15} n/(cm^2· s).

**) 90% of assymptotic level.

Harmonized Nuclear Energy System

ROSATOM



ENC: Excess Neutron Cost

$$ENC = \frac{E_f^{NS} + E^{NS}}{\Delta n_{ex}}$$

Energy associated with generation of one excess neutron

EUF: Energy Utilization Factor

$$EUF = \frac{E_f^{net}}{E_f^{net} + E_f^{NS} + E^{NS}}$$

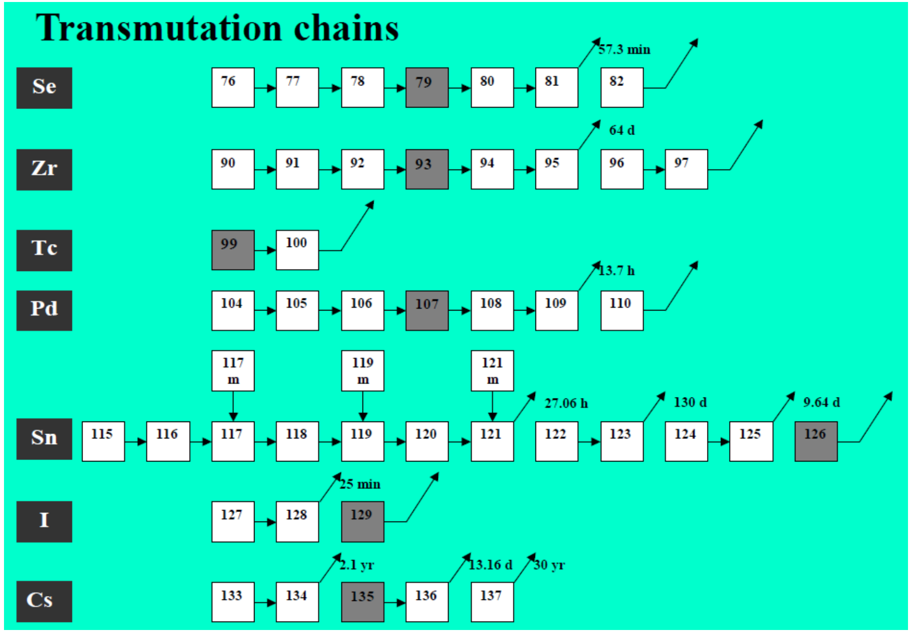
$$EUF = \frac{1}{1 + ENC\,\frac{n_r}{e_f}}$$

Neutron requirements for transmutation (n/f)

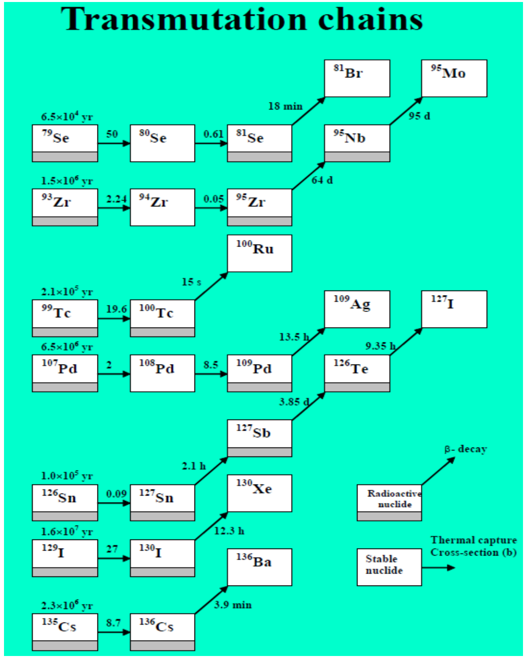
Fission Energy (200 MeV)

Neutron Requirements for Fission Products Transmutation

No Isotope Separation
(1.0 n/fission)

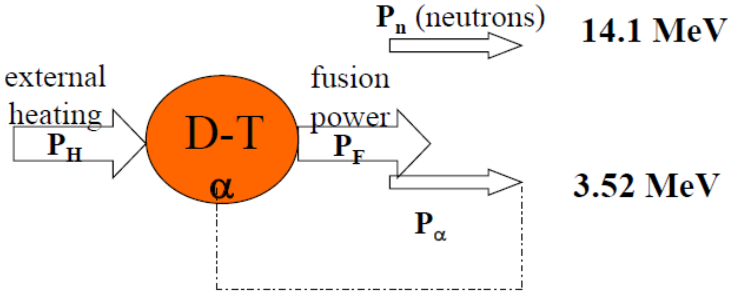


Isotope Separation Option
(0.3 n/fission)



Fusion Neutron Source

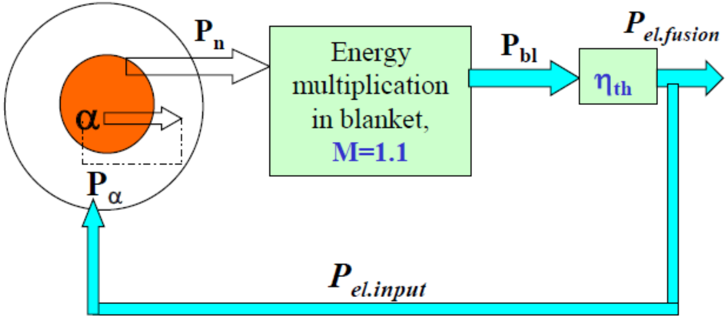
Essence of D-T fusion process



Thermal utilization efficiency:

$$Q_{th} = \frac{P_{fusion}}{P_{thermal\ input}}$$

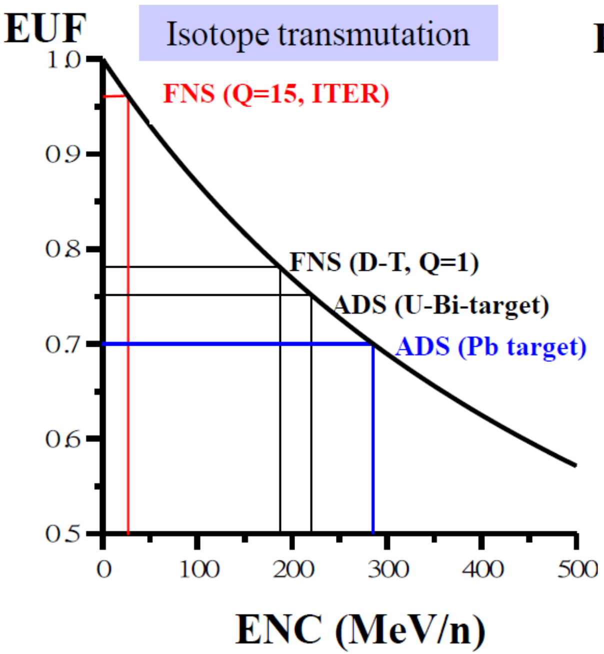
Energy flows in Fusion Neutron Source

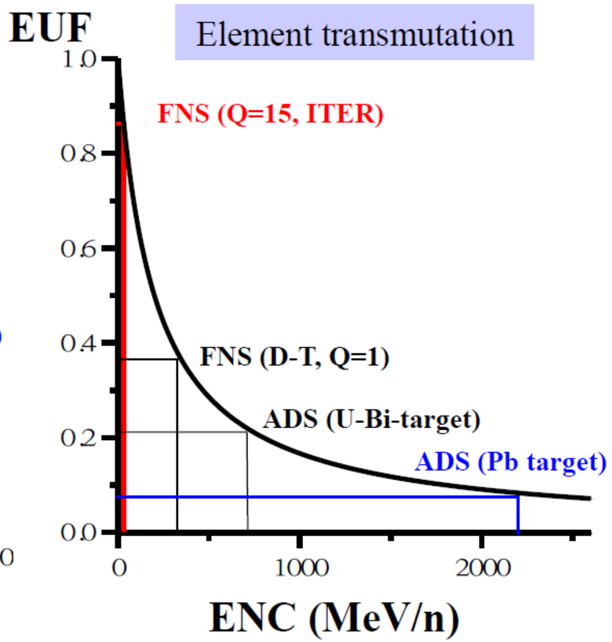


Break-even energy conditions (energy self-sustaining in FNS):

$$Q_{th}^{be} = \frac{1}{\eta_{th}\eta_{heating}} = 5$$

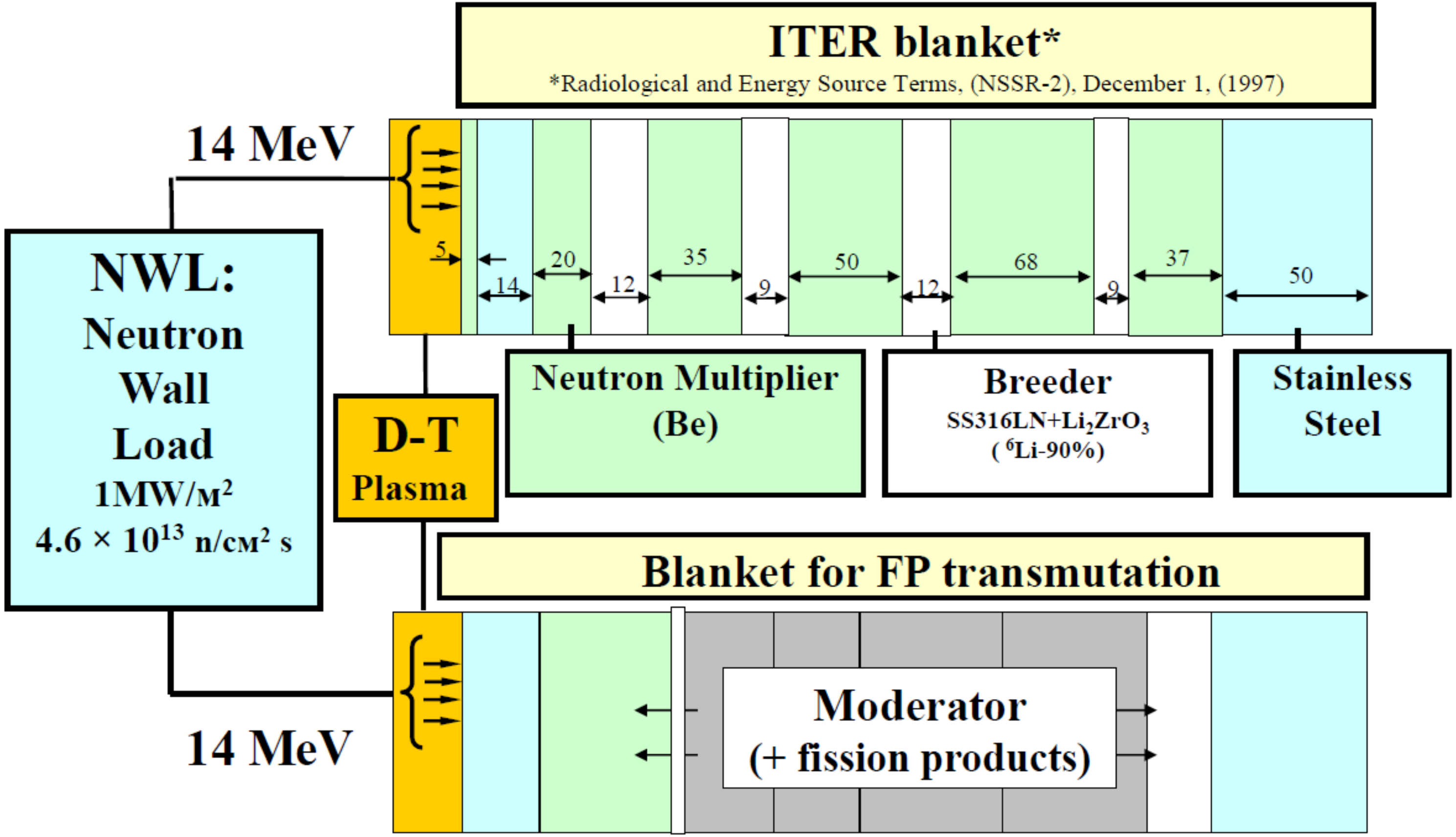
Energy Utilization Factor as a Function of Excess Neutron Cost



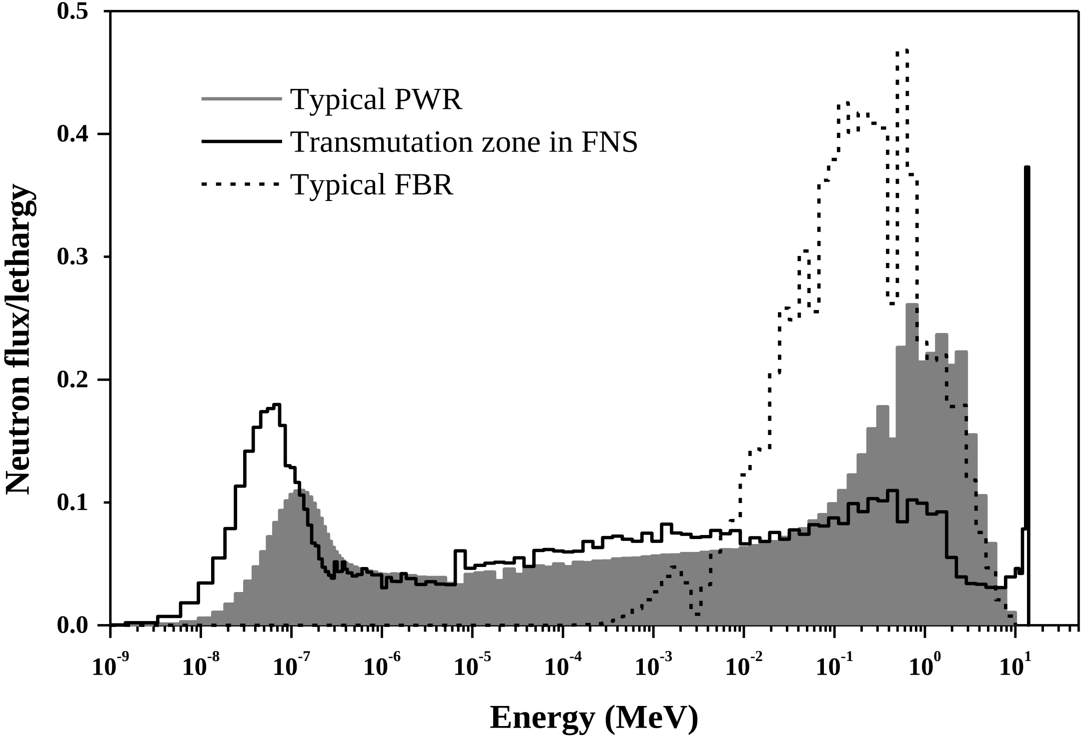


A. Chmelev, et al: Multi-Component Nuclear Energy System: Possible Ways to Meet Requirement of Self-Consistency; Progress in Nuclear Energy, Vol. 32, No. 3/4, p.659-663, 1998

FNS Blanket Configurations

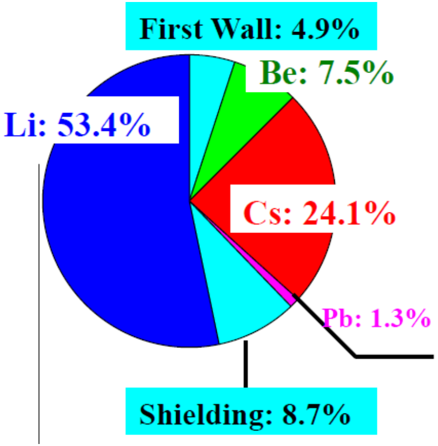


Elemental Cesium Transmutation



V.Apse, et al, Analysis of transient period till equilibrium transmutation of elemental cesium, Nuclear Energetics, 1999, v.4, p.83-87

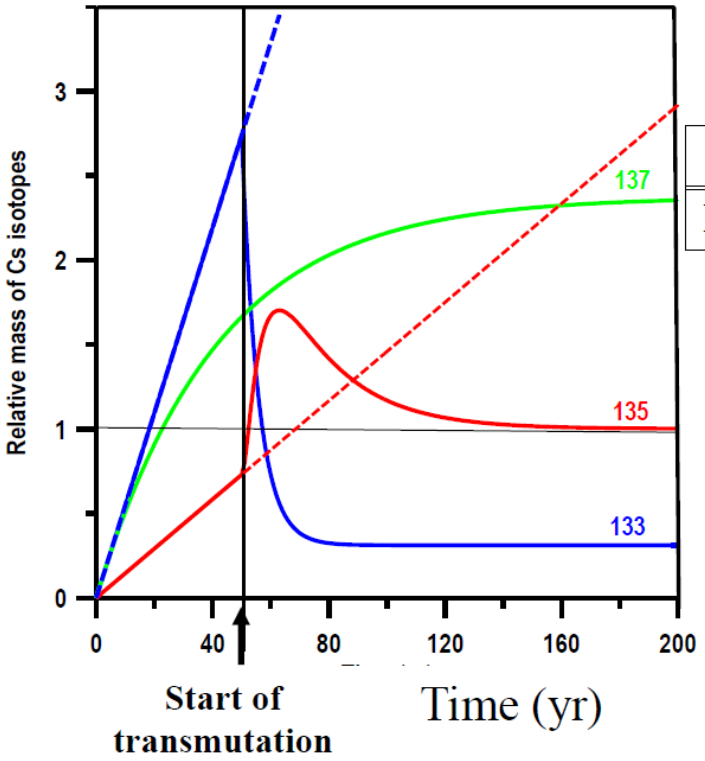
Neutron Balance



Mean life-time of Cs-135

Fast Spectrum(0.2 MeV) Flux: 1.0+15 (n/cм^2·s)	450
Therm. Spectrum(1 eV) Flux: 1.0+14 (n/cм^2·s)	240
FNS Flux: 4.5+14 (n/cм^2·s)	22

FNS Blanket Configurations

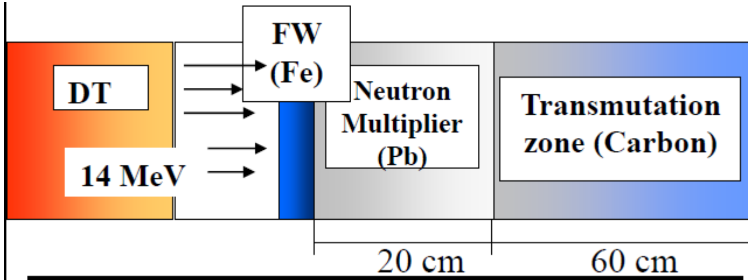


Cs vector				
	133	134	135	137
Feeding	0.45	-	0.12	0.43
Equilibrium	0.08	0.02	0.27	0.63

Transmutation efficiency

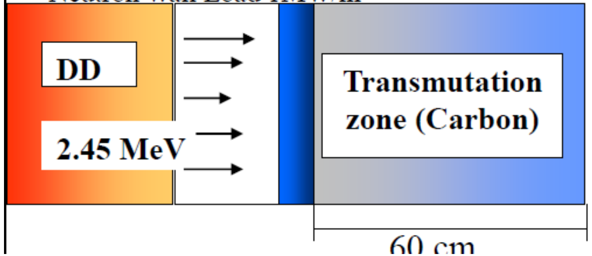
Loading (t)	44.2
Transmutation rate (t/yr)	1.6
PWR-park supported (GW_{el})	21
Fission Utilization Factor (%)	97

Specifics of FNS Neutronics

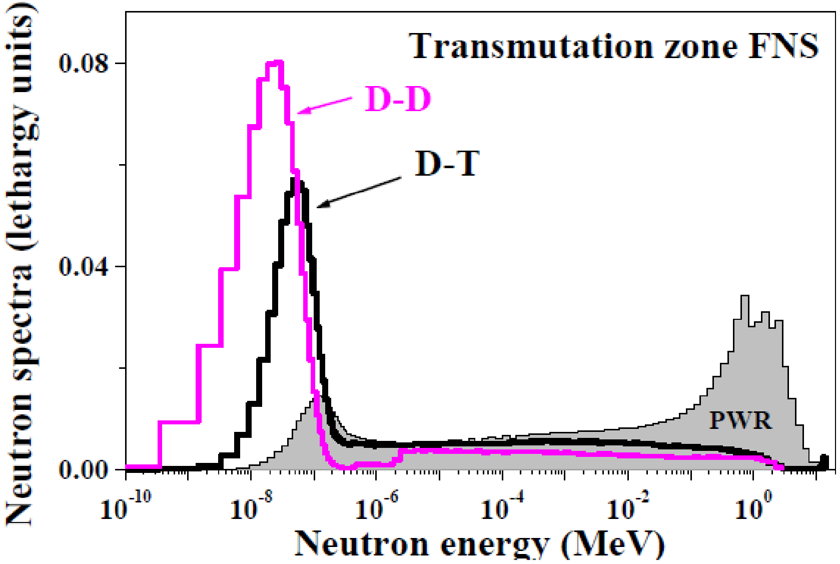


Plasma Option	Average energy (MeV)		Neutron flux (n/sm^{2}s) *	
	First Wall	Transmutation zone	First Wall	Transmutation zone
D-T	1.44	1.9×10^{-2}	7.2×10^{14}	2.1×10^{14}
D-D	0.56	2.7×10^{-4}	4.3×10^{15}	1.5×10^{15}

* Neutron Wall Load 1MW/m^2



Flexibility in forming neutron spectrum



A.Stankovskii, et al, Transmutation of Long-Lived Fission Products Driven by DT and DD-Fusion: Specific Neutronics and Radiological Consequences; Fusion Science and Technology, 143, 569-579 (2003)

Conclusions

- Fusion neutron source (FNS) is flexible in shaping neutron spectrum
- FNS reveals excellent waste transmutation characteristics
- FNS application for waste transmutation is a way to “clean energy system”
- Fission-Fusion harmonization is achieved with a small fusion energy impact on nuclear energy system

Thank you for your attention

Vladimir ARTISYUK
Advisor to Director General

Mob.: +7 (915) 896 94 84
E-mail: VVArtisyuk@rosatom.ru
www.rosatom.com

07.06.2022