ROSATOM

Reactor Physics of Innovative NES

Joint ICTP - IAEA Workshop on Physics and Technology of Innovative Nuclear Energy Systems

12 - 16 December 2022

An ICTP - IAEA Hybrid meeting Trieste, Italy

Vladimir ARTISYUK

Content

Factors Affecting Nuclear Development

2015: UN Sustainable Development Goals 2030

2015: Paris Agreements

2018: International Platform on Climate Change Report

2019: COVID-19

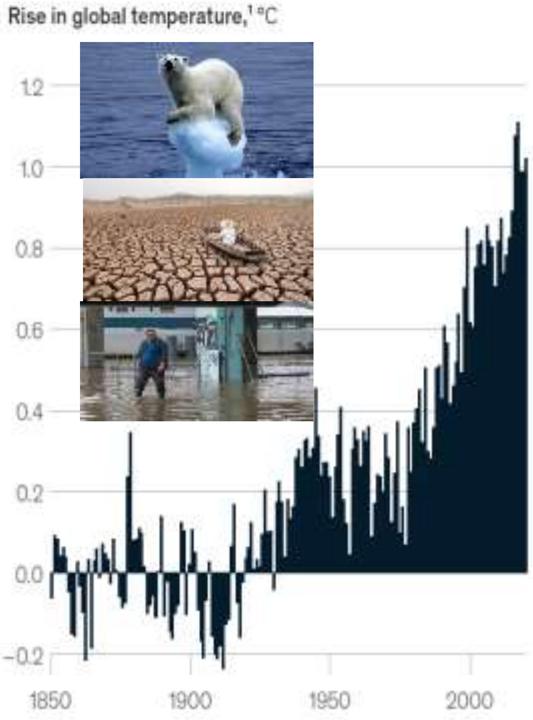
2019-22: EC Taxonomy

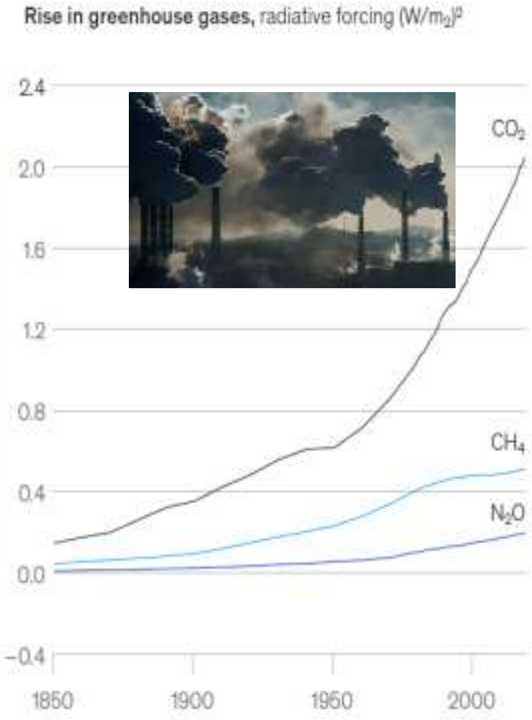

ipcc

Global Warming of 1.5°C

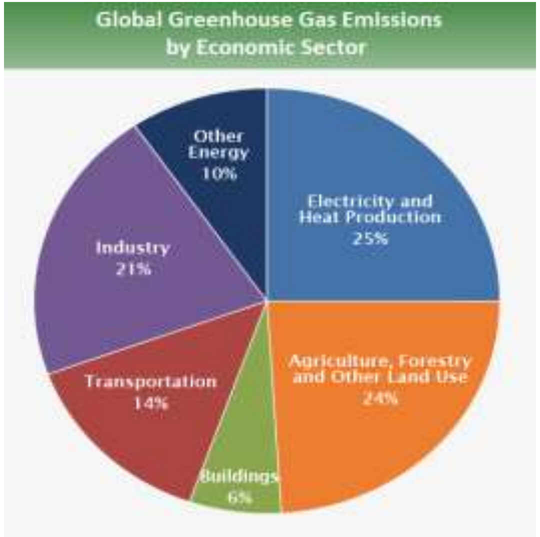

EU Taxonomy

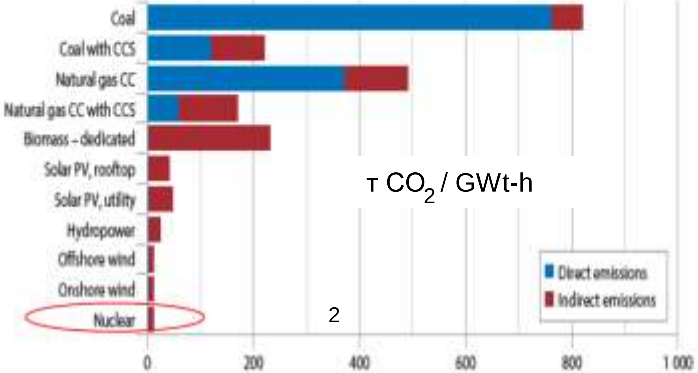
Global Context


Rise in global temperature,[1] °C


Rise in greenhouse gases, radiative forcing (W/m$_2$)[2]

From: McKinsey Sustainability, Curbing Methane Emission, Sept 2021




τ CO$_2$ / GWt-h

Source: IPCC (2014)

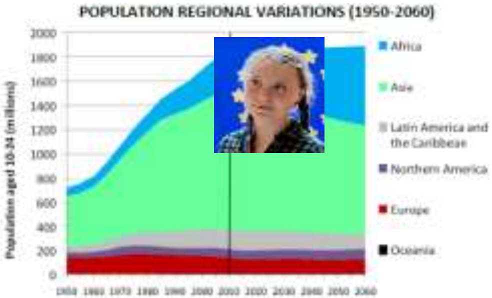
UN Sustainable Goals: From declaration to challenges

UN Sustainable Development Summit 25-27.09 2015 (UN HQ)

73rd UN General Assembly 24.09 2018 (UN HQ)

UN SG Ban Ki-moon
2007- 2016

UN SG A. Guterres
2017-



There are over 1.8 billion young people in the world today, 90 per cent of whom live in developing countries

IEA Director Dr F.Birol
18.04.2020

18.04.2020

The IEA's *Africa Energy Outlook 2019* showed how the energy sector can help Africa realise its growth ambitions while also delivering key sustainable development goals by 2030, including **full access to electricity** and **clean cooking facilities**.

The World Bank forecast earlier this month that Sub-Saharan Africa will in 2020 experience its first recession in 25 years, with the region's economy contracting between 2.1% and 5.1% as a result of the Covid-19 crisis. **This will make key sustainable development goals, such as increasing access to electricity and clean cooking, that much harder to achieve**.

The proportion of the world's young people between the ages of 12-24 years living in Africa is expected to rise from 18 % in 2012 to 28 %by 2040

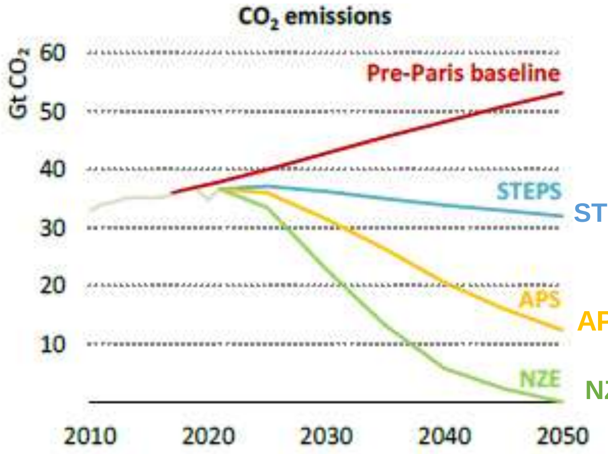
Influential Factors and Prognosis

2018: International Platform on Climate Change Report

share in power system 2030 / 2050 (% rel. to 2010)	Scenario #			
	1	2	3	4
Renewables in electricity	60/77	58/81	48/63	25/70
Primary energy from coal	-78/-97	-61/-77	-75/-73	-59/-97
Primary energy from oil	-37/-87	-13/-50	-3/-81	86/-32
Primary energy from gas	-25/-74	-20/-53	33/21	37/-48
Primary energy from nuclear	59/150	83/98	98/501	106/468

GWt el

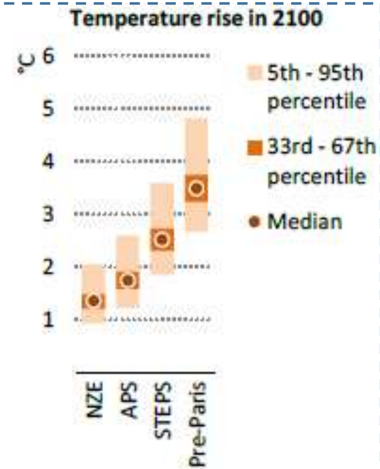
Influential Factors and Prognosis

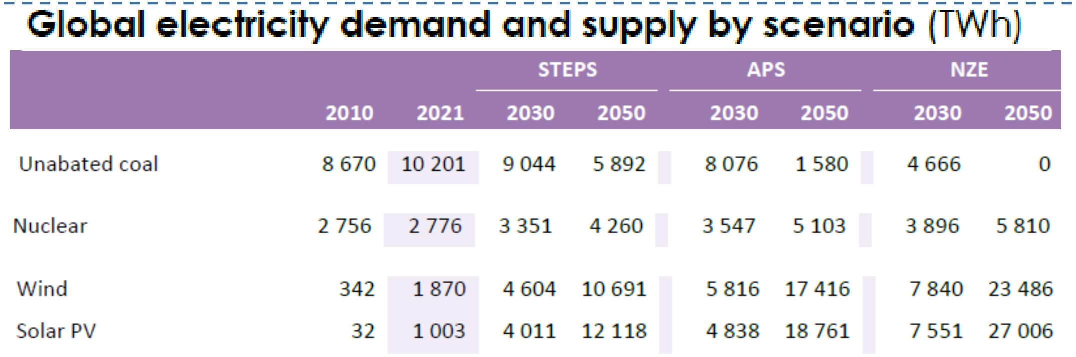


STEPS: Stated Policies Scenario

APS: Announced Pledges Scenario

NZE: Net Zero Emissions by 2050





Global electricity demand and supply by scenario (TWh)

			STEPS		APS		NZE	
	2010	2021	2030	2050	2030	2050	2030	2050
Unabated coal	8 670	10 201	9 044	5 892	8 076	1 580	4 666	0
Nuclear	2 756	2 776	3 351	4 260	3 547	5 103	3 896	5 810
Wind	342	1 870	4 604	10 691	5 816	17 416	7 840	23 486
Solar PV	32	1 003	4 011	12 118	4 838	18 761	7 551	27 006

STEPS: completion of 120 GW of new nuclear capacity over the 2022-30 period, another 300 GW of new reactors (the equivalent of almost three-quarters of the current global fleet) between 2030 and 2050 in over 30 countries.

NZE: 24 GW of capacity added each year between 2022 and 2050 more than doubles nuclear power capacity by 2050.

Complementary Climate Delegated Act

2 February 2022

Nuclear related activities included in the Taxonomy:

Research, development and deployment of advanced technologies (“Generation IV”) that minimise waste and improve safety standards

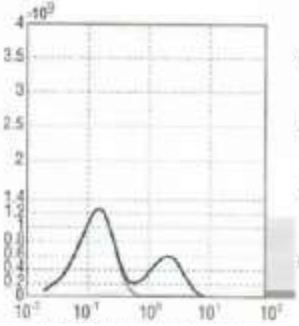
New nuclear plant projects with existing technologies for energy generation of electricity or heat (“Generation III+”) [until 2045]

Upgrades and modifications of existing nuclear plants for lifetime extension purposes [until 2040]

World Energy Consumption

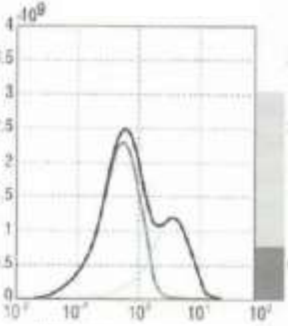
E.Velikhov et al
Russia and World Power in 21 Century, 2006

3862 Mtoe



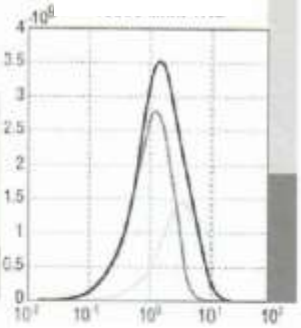
Mtoe per capita
1965

10224 Mtoe

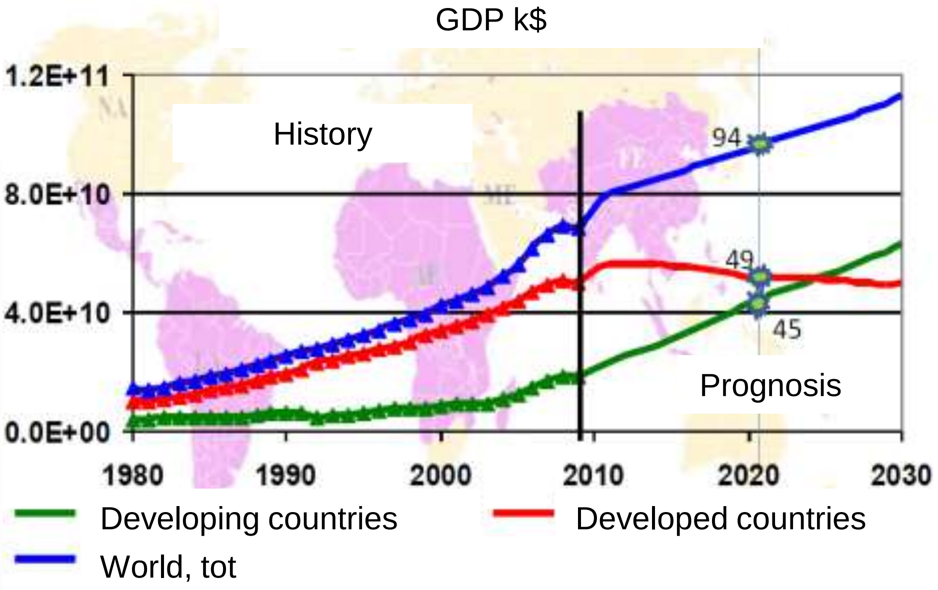


Mtoe per capita
2004

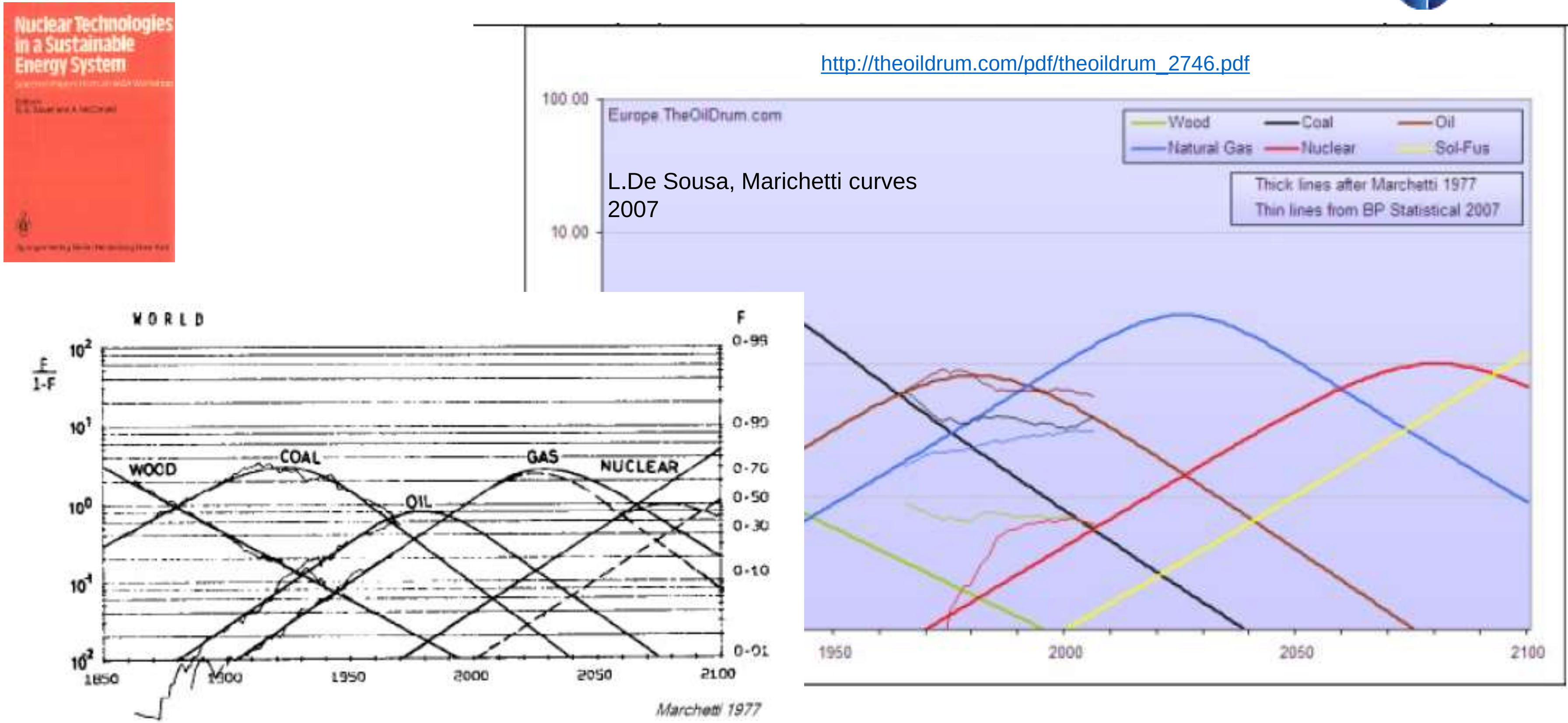
15000 Mtoe



Mtoe per capita
2025 (prognosis)



Energy Substitution Modelling

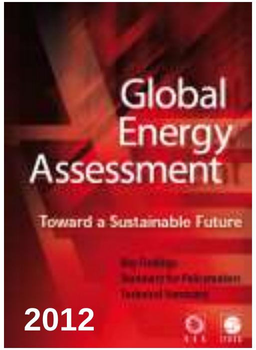


Nuclear Technologies in a Sustainable Energy System

http://theoildrum.com/pdf/theoildrum_2746.pdf

L.De Sousa, Marichetti curves 2007

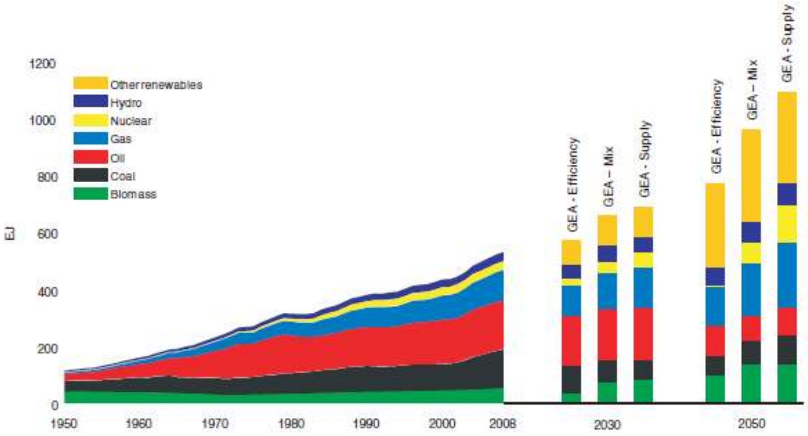
Influential Factors and Prognosis

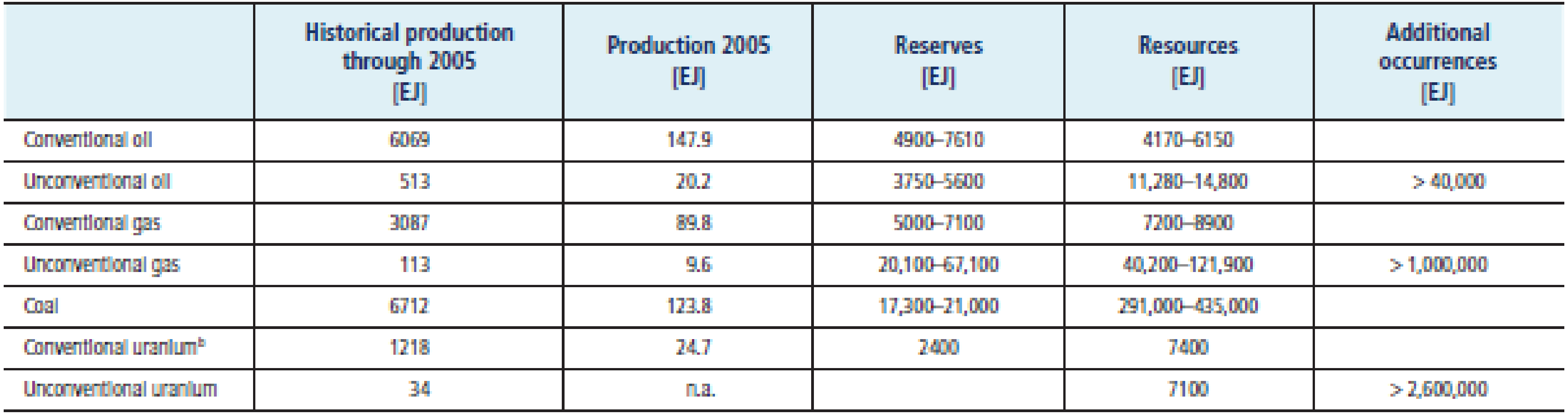


Global Energy Assessment

Toward a Sustainable Future

2012





	Historical production through 2005 [EJ]	Production 2005 [EJ]	Reserves [EJ]	Resources [EJ]	Additional occurrences [EJ]
Conventional oil	6069	147.9	4900–7610	4170–6150	
Unconventional oil	513	20.2	3750–5600	11,280–14,800	> 40,000
Conventional gas	3087	89.8	5000–7100	7200–8900	
Unconventional gas	113	9.6	20,100–67,100	40,200–121,900	> 1,000,000
Coal	6712	123.8	17,300–21,000	291,000–435,000	
Conventional uranium[b]	1218	24.7	2400	7400	
Unconventional uranium	34	n.a.		7100	> 2,600,000

Reserves, resources, and occurrences of uranium are based on a once-through fuel cycle operation. Closed fuel cycles and breeding technology would increase the uranium resource dimension 50–60 fold. Thorium-based fuel cycles would enlarge the fissile-resource base further.

Trends in Assessing Material Balance

From Fuel intensive through Manufacturing Intensive to Mineral Intensive System

Large Scale

Carbon free

SMR

Complementary to Renewables

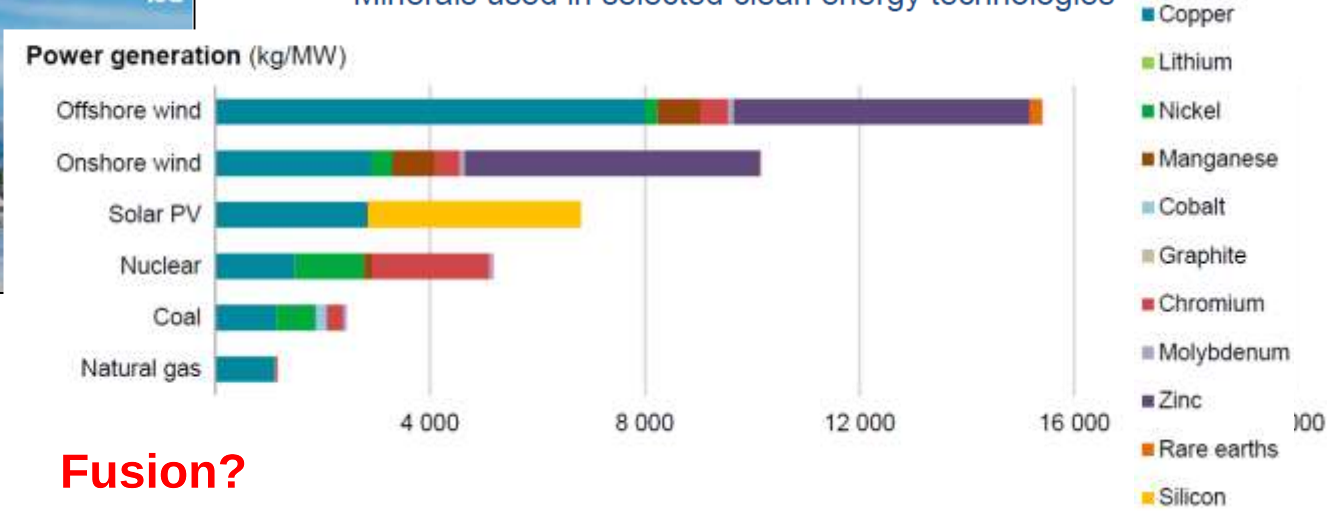
Fusion

Wasteless

The Role of Critical Minerals in Clean Energy Transitions

May 2021

Minerals used in selected clean energy technologies



Fusion?

OECD/NEA Reaction

ROSATOM

Multi-sector workshop on innovative regulation: Challenges and benefits of harmonising the licensing process for emerging technologies

23 December 2020

“But the most important thing is that **we have to get this done quickly**. If our objective is to meet the climate challenge, we need to move very quickly. The decisions by governments and industry around the world are being made today. And if we don’t have the technologies and the regulations in place to support advanced nuclear technologies over the next decade or 15 years, it’s going to be too late. **This is not a long-term project; we have to do this now**. And we have to that by working together. From our standpoint at the NEA, we look forward to helping to facilitate that as we go forward.”

William D. Magwood, IV, NEA Director-General

https://oecd-nea.org/jcms/pl_52743/multi-sector-workshop-on-innovative-regulation-challenges-and-benefits-of-harmonising-the-licensing-process-for-emerging-technologies

From Proceedings of National Academy of Sciences (USA)

PNAS RESEARCH ARTICLE | ENVIRONMENTAL SCIENCES OPEN ACCESS

Nuclear waste from small modular reactors

Lindsay M. Krall[a,1,2], Allison M. Macfarlane[b], and Rodney C. Ewing[a]

Edited by Eric J. Schelter, University of Pennsylvania, Philadelphia, PA; received June 26, 2021; accepted March 17, 2022 by Editorial Board Member Peter J. Rossky

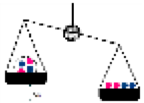
Results reveal that water-, molten salt–, and sodium-cooled SMR designs will increase the volume of nuclear waste in need of management and disposal by factors of 2 to 30.

Volume is not the most important evaluation metric; rather, geologic repository performance is driven by the decay heat power and the (radio-)chemistry of spent nuclear fuel, for which SMRs provide no benefit. SMRs will not reduce the generation of geochemically mobile 129I, 99Tc, and 79Se fission products, which are important dose contributors for most repository designs.

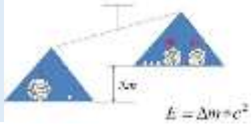
SMRs will exacerbate the challenges of nuclear waste management and disposal.

May 31, 2022119 (23) e2111833119 https://doi.org/10.1073/pnas.2111833119

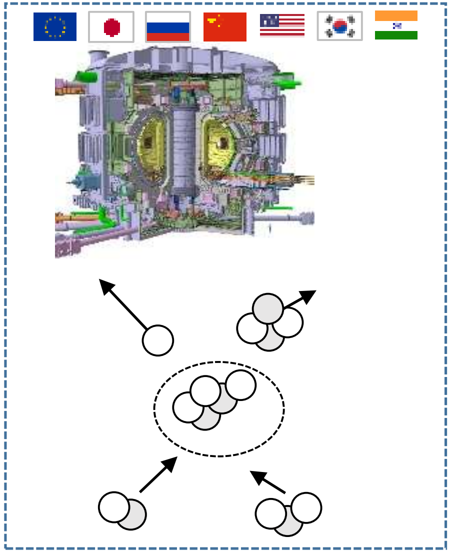
Binding Energy



Fact:
The mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it.

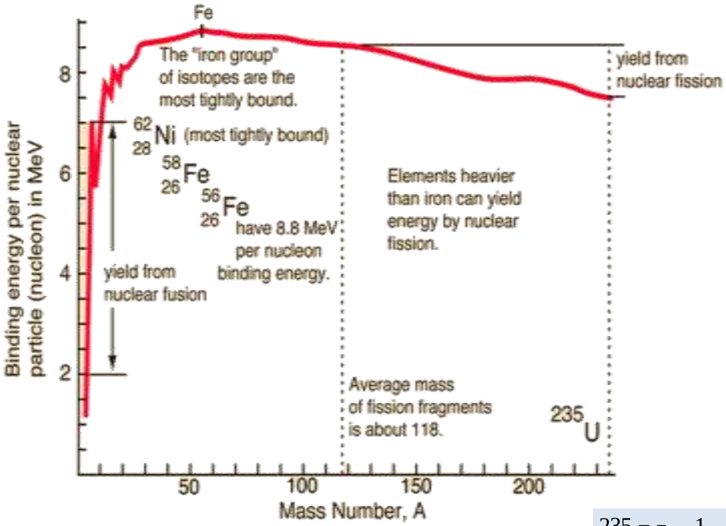


The difference is a measure of the nuclear **binding energy** which holds the nucleus together.



$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}He + {}^{1}_{0}\mathrm{n} $$

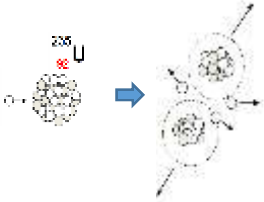
~ 20 MeV



Uranium isotopes

Natural: 0,72 99,28 %

$^{235}_{92}\mathrm{U}$ $^{238}_{92}\mathrm{U}$

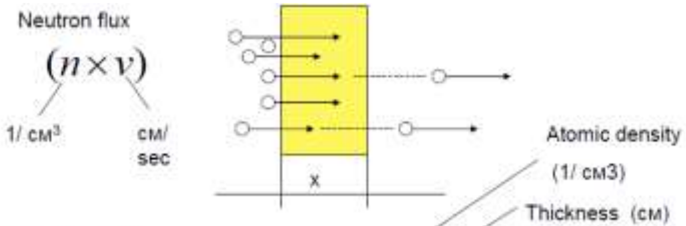


Kinetic energy of fission products

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}U \rightarrow {}^{90}_{37}\mathrm{Rb} + {}^{143}_{55}\mathrm{Cs} + 3{}^{1}_{0}\mathrm{n} $$

~ 200 MeV

Cross-Section: Definition



Reaction rate

(number of reactions per second per cc)

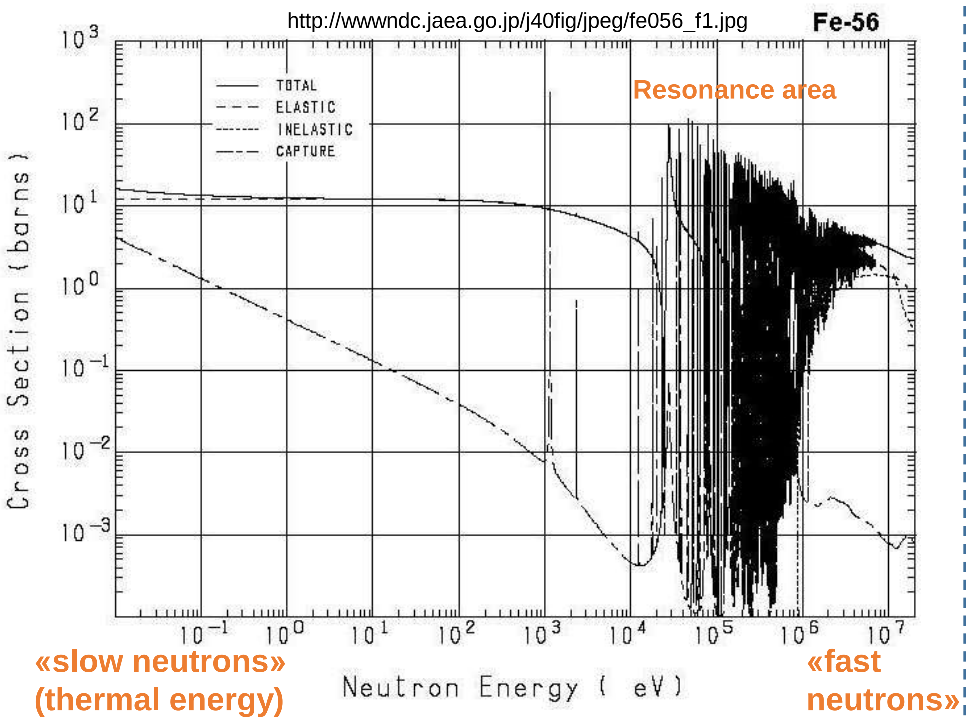
$$N \sim \gamma\, x\, (n \times v)$$

1/ (sec см³)

$$N = \sigma\, \gamma\, x\, (n \times v)$$

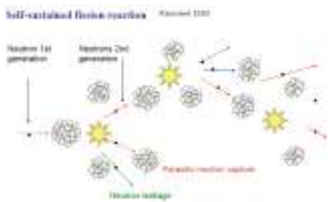
Microscopic cross-section – determines the reaction rate

Units: 1 barn = 10^{-24} см²

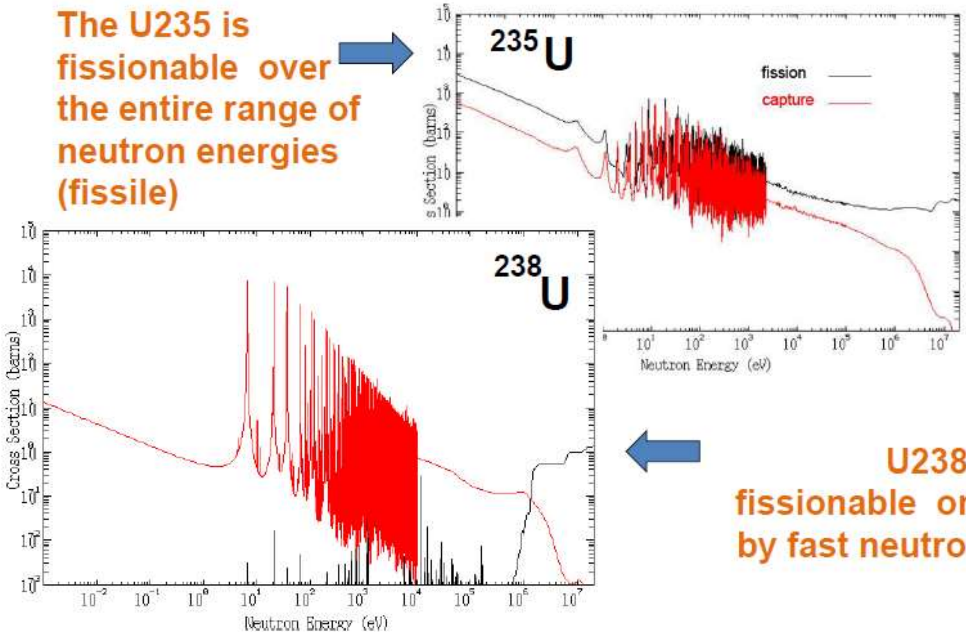

http://wwwndc.jaea.go.jp/j40fig/jpeg/fe056_f1.jpg

Fe-56

Cross-Sections of Uranium Isotopes

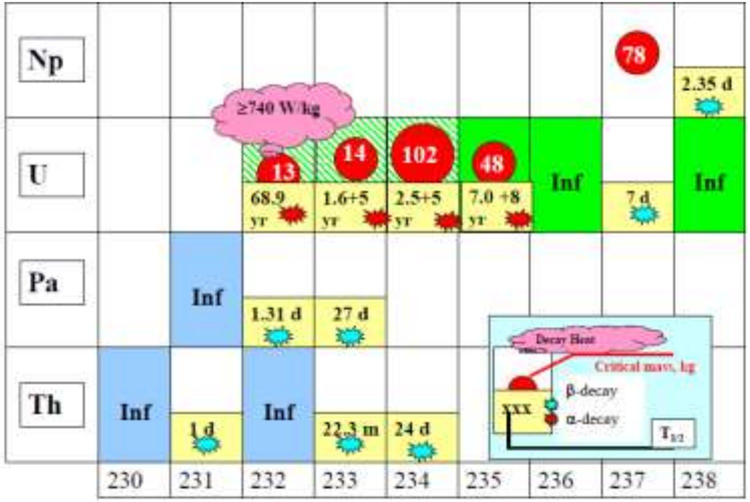


The U235 is fissionable over the entire range of neutron energies (fissile)



U238 is fissionable only by fast neutrons

Critical mass of some selected isotopes



	230	231	232	233	234	235	236	237	238
Np								78	2.35 d
U			13 68.9 yr	14 1.6+5 yr	102 2.5+5 yr	48 7.0 +8 yr	Inf	7 d	Inf
Pa		Inf	1.31 d	27 d					
Th	Inf	1 d	Inf	22.3 m	24 d				

Fission Neutron Release and Fission Spectrum

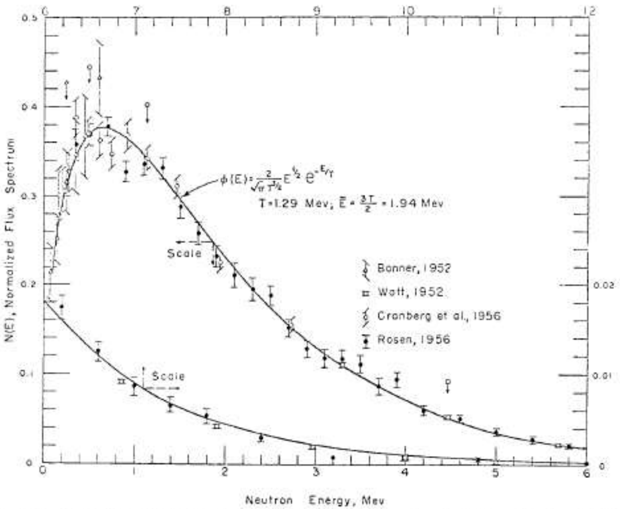
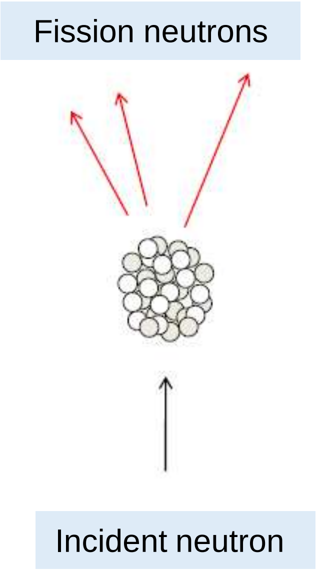


Fig. 3–1. Experimental neutron energy spectrum from thermal-neutron-induced fission of U^{235}. Methods of measurement were: Bonner, cloud chamber; Watt, proton recoil; Cranberg, time-of-flight; Rosen, nuclear emulsion. (See text for references.) The solid line shows the best fitted Maxwellian spectral function. Arrows indicate normalization point for each set of data. (After J. A. Grundl [20].)

PHYSICS OF
NUCLEAR KINETICS

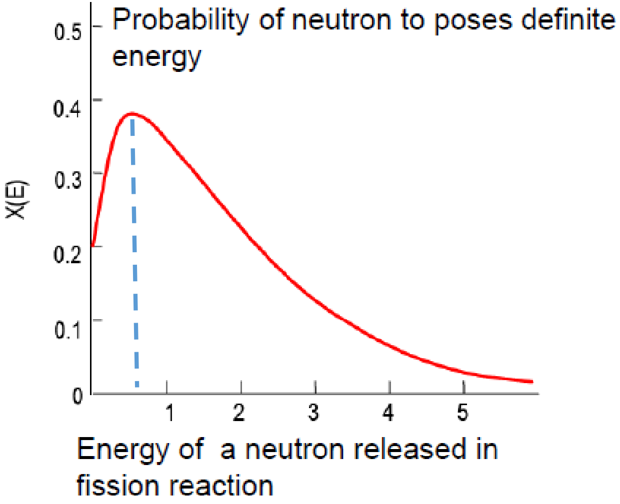
G. ROBERT KEEPIN

1964

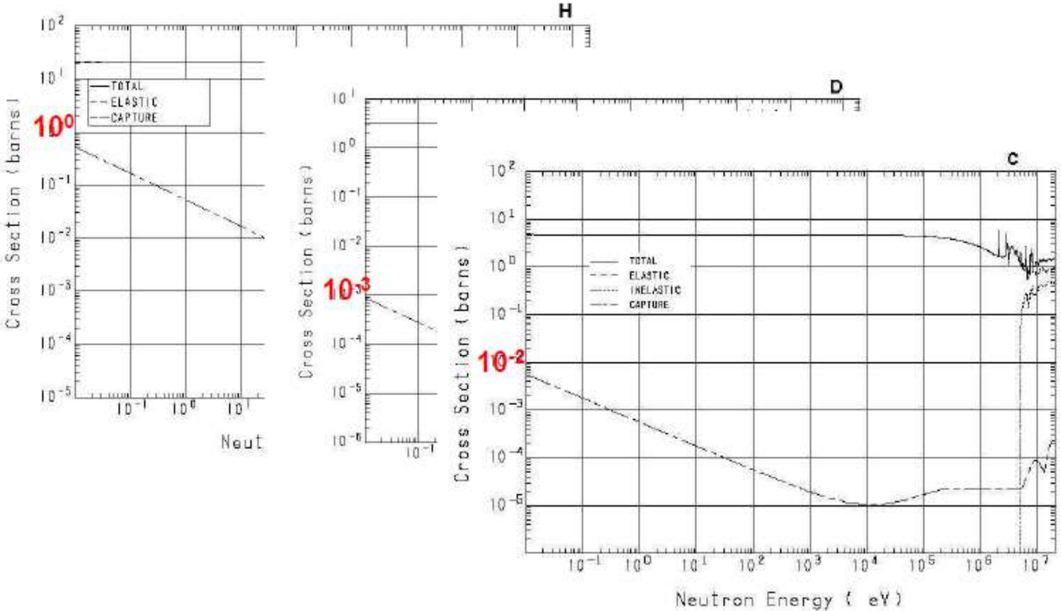


Fission neutrons

Incident neutron



Capture Cross Sections of Light Nuclides and Reactor Types



Uranium enrichment:

CANDU -650:
0.72%
(natural)

RBMK -1000:
1.8%

VVER-1200/PWR:
3-5%

FNPP 2X35:
18,7%

From the IAEA Statute

Article III Functions

5 To establish and administer safeguards designed to ensure that special fissionable and other materials, services, equipment, facilities, and information made available by the Agency or at its request or under its supervision or control are not used in such a way as to further any military purpose; and to apply safeguards, at the request of the parties, to any bilateral or multilateral arrangement, or at the request of a State, to any of that State's activities in the field of atomic energy

Article XX Definitions

1. The term "special fissionable material" means plutonium-239; uranium-233; uranium enriched in the isotopes 235 or 233; any material containing one or more of the foregoing; and such other fissionable material as the Board of Governors shall from time to time determine; but the term "special fissionable material" does not include source material.

2. The term "uranium enriched in the isotopes 235 or 233" means uranium containing the isotopes 235 or 233 or both in an amount such that the abundance ratio of the sum of these isotopes to the isotope 238 is greater than the ratio of the isotope 235 to the isotope 238 occurring in nature.

3. The term "source material" means uranium containing the mixture of isotopes occurring in nature; uranium depleted in the isotope 235; thorium; any of the foregoing in the form of metal, alloy, chemical compound, or concentrate;

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$$^{1}n + {}^{232}Th \rightarrow {}^{233}U$$

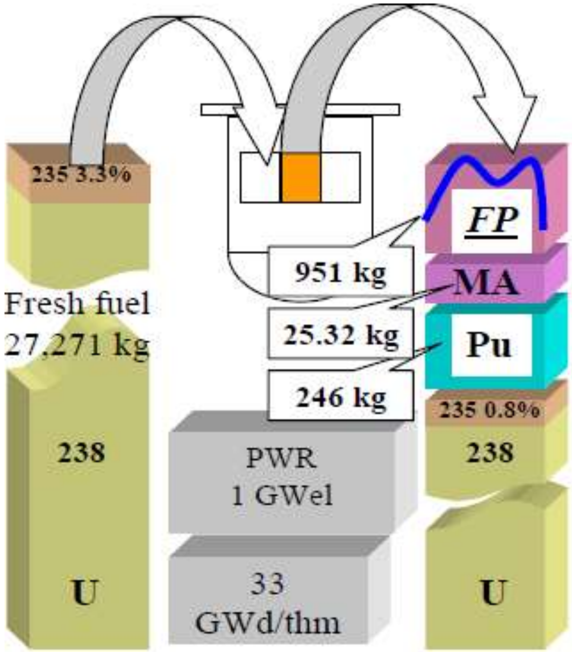
$$^{1}n + {}^{238}U \rightarrow {}^{239}Pu$$

Significant Quantity and Spent Fuel

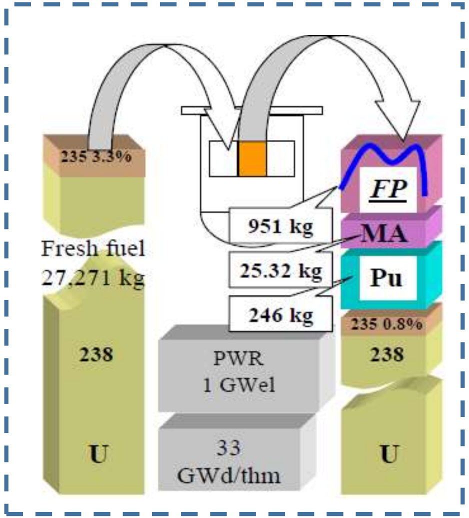
SQ: The approximate amount of *nuclear material* for which the possibility of manufacturing a nuclear explosive device cannot be excluded. SQs take into account unavoidable losses due to conversion and manufacturing processes and should not be confused with critical masses.

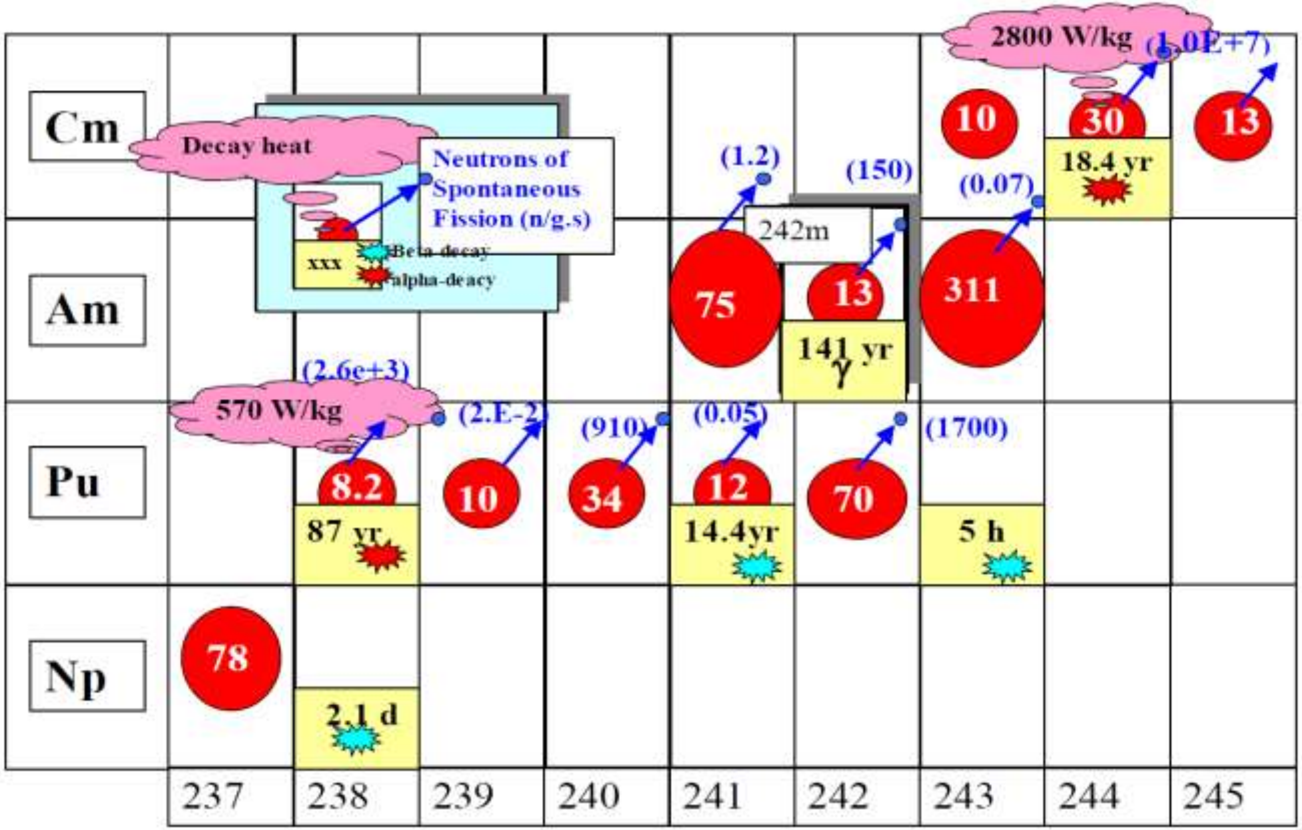
Direct use nuclear material	
Plutonium	**8 kg plutonium** Containing less than 80% Pu-238
^{233}U	**8 kg ^{233}U**
High enriched uranium (U >= 20%)	**25 kg ^{235}U**

Indirect use nuclear material	
Uranium (^{235}U < 20%) **(or 10 t natural U or 20 t odepleted U)**	**75 kg ^{235}U**
Thorium	**20 t thorium**

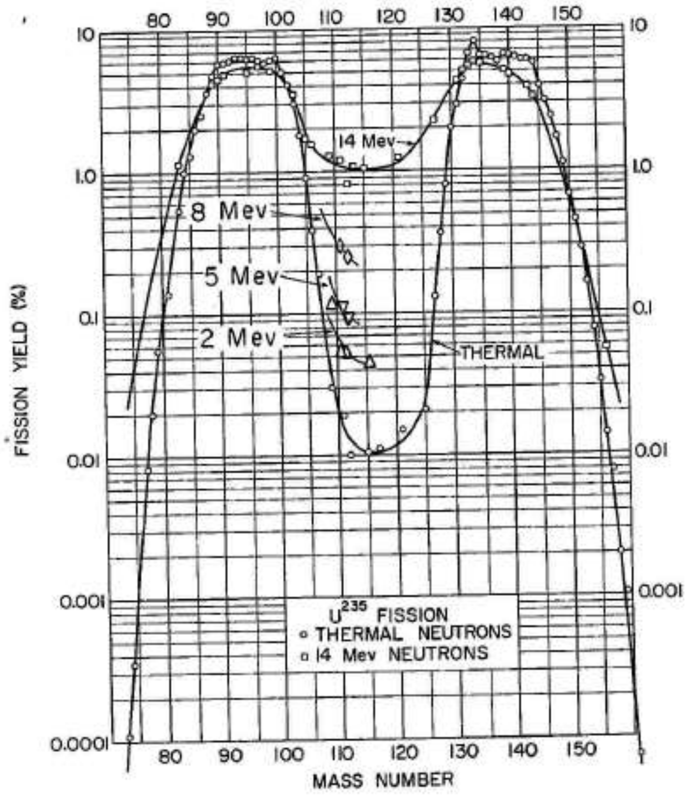


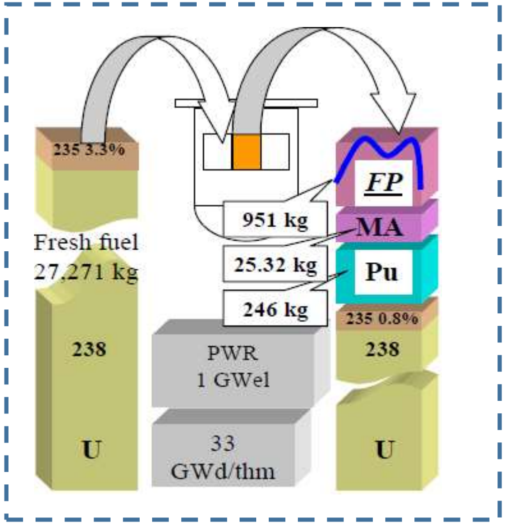
Properties of Minor Actinides



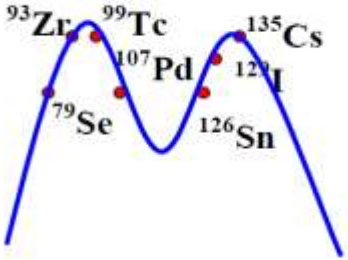


Fission Products





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



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

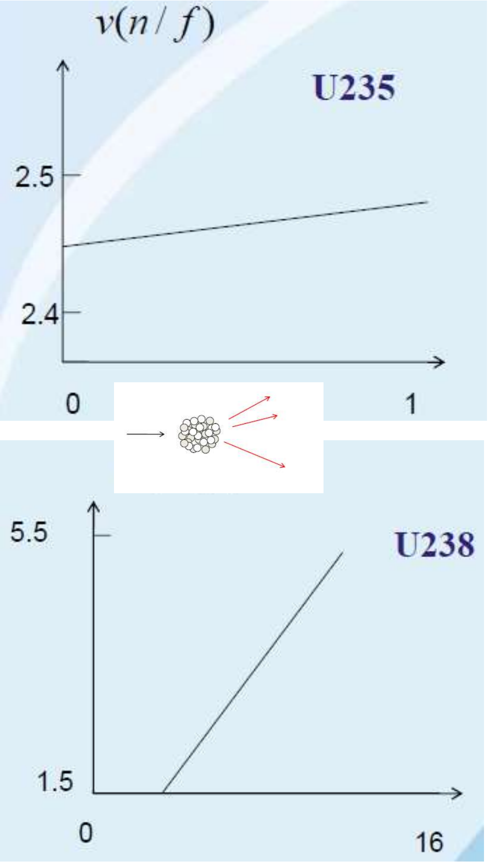
$^{237}Np: (n,\gamma)^{238}Np \rightarrow {}^{238}Pu$

$^{241}Am: (n,\gamma)^{242}Am \rightarrow {}^{242}Cm \rightarrow {}^{238}Pu$

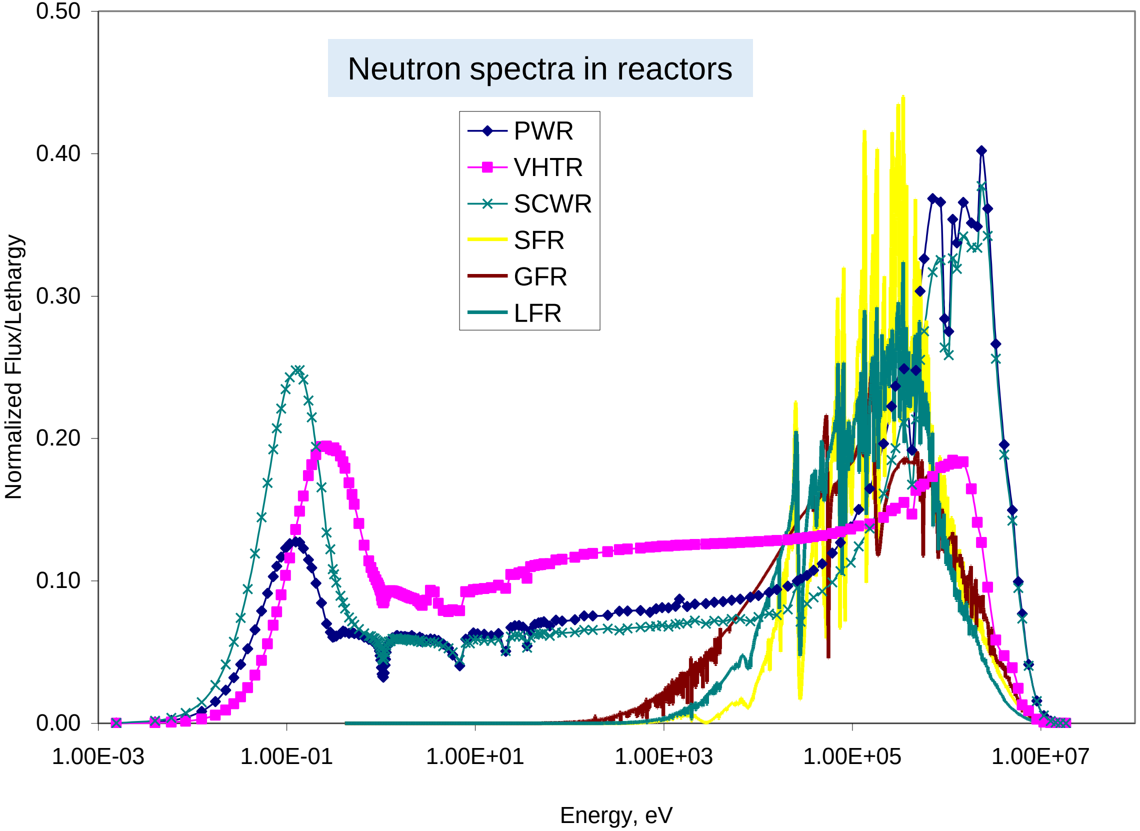
Pu - recycle ➡ Energy production (&complete use of uranium)

U - recyle ➡ Energy production (&uranium saving)

Number of Fission Neutrons and Neutron Spectra

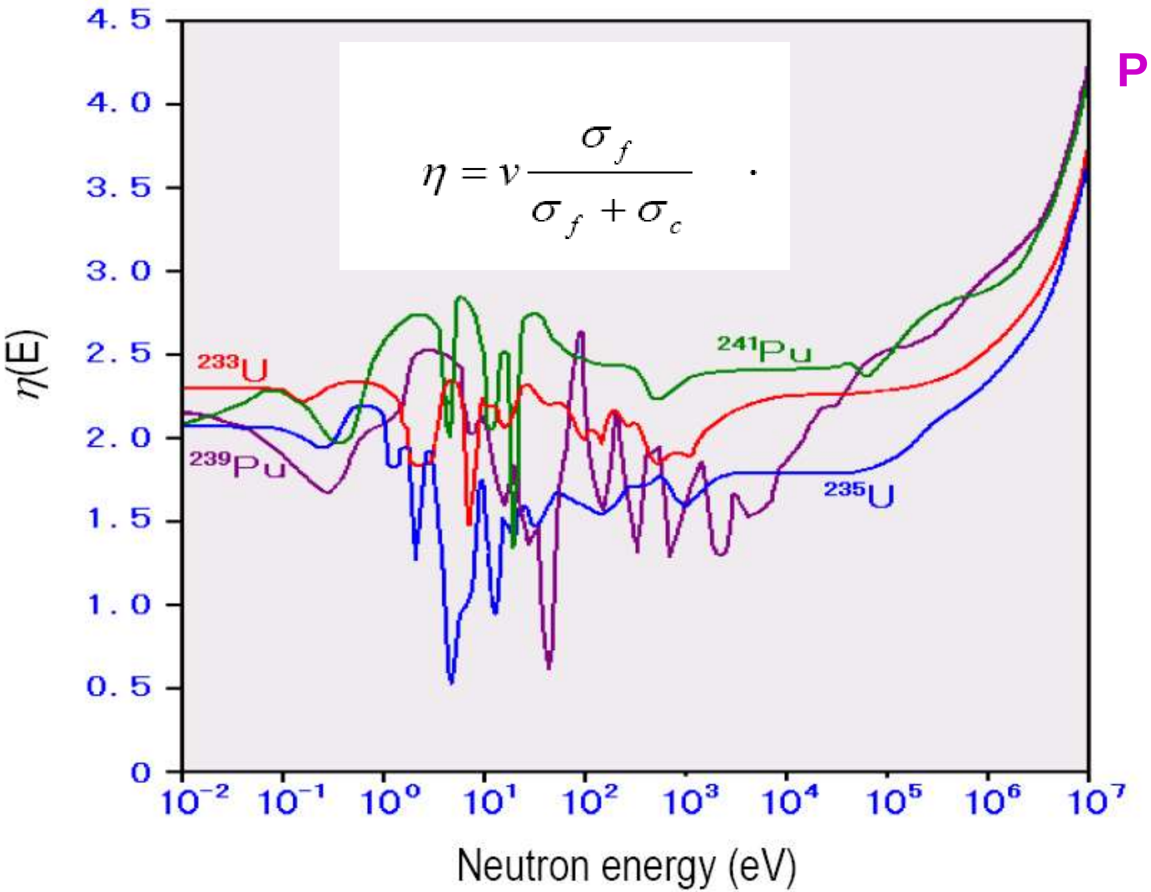


Energy of incident neutron (MeV)



GEN-IV systems and the related fuel strategies, F.Storer (CEA), EU-Rosatom Meeting, Obninsk 18-19 June,2008

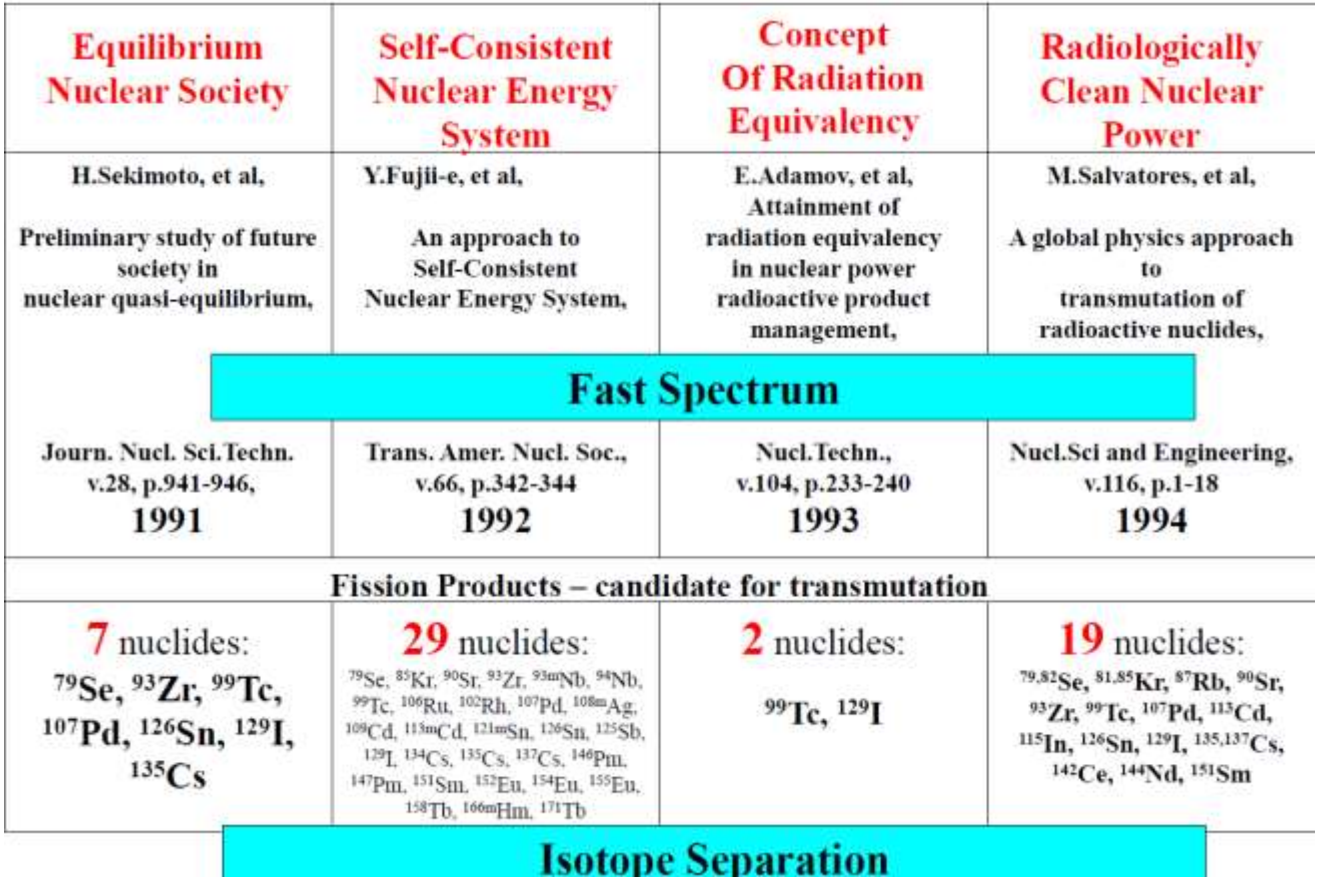
Neutron Release per Absorption



$$\eta = \nu \frac{\sigma_f}{\sigma_f + \sigma_c} \quad .$$

Pu-239

Fast Reactors: Waste Cleaning Machines



Equilibrium Nuclear Society	Self-Consistent Nuclear Energy System	Concept Of Radiation Equivalency	Radiologically Clean Nuclear Power
H.Sekimoto, et al, Preliminary study of future society in nuclear quasi-equilibrium,	Y.Fujii-e, et al, An approach to Self-Consistent Nuclear Energy System,	E.Adamov, et al, Attainment of radiation equivalency in nuclear power radioactive product management,	M.Salvatores, et al, A global physics approach to transmutation of radioactive nuclides,
Fast Spectrum			
Journ. Nucl. Sci.Techn. v.28, p.941-946, 1991	Trans. Amer. Nucl. Soc., v.66, p.342-344 1992	Nucl.Techn., v.104, p.233-240 1993	Nucl.Sci and Engineering, v.116, p.1-18 1994
Fission Products – candidate for transmutation			
7 nuclides: ^{79}Se, ^{93}Zr, ^{99}Tc, ^{107}Pd, ^{126}Sn, ^{129}I, ^{135}Cs	29 nuclides: ^{79}Se, ^{85}Kr, ^{90}Sr, ^{93}Zr, ^{93m}Nb, ^{94}Nb, ^{99}Tc, ^{106}Ru, ^{102}Rh, ^{107}Pd, ^{108m}Ag, ^{109}Cd, ^{113m}Cd, ^{121m}Sn, ^{126}Sn, ^{125}Sb, ^{129}I, ^{134}Cs, ^{135}Cs, ^{137}Cs, ^{146}Pm, ^{147}Pm, ^{151}Sm, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{158}Tb, ^{166m}Hm, ^{171}Tb	2 nuclides: ^{99}Tc, ^{129}I	19 nuclides: ^{79,82}Se, ^{81,85}Kr, ^{87}Rb, ^{90}Sr, ^{93}Zr, ^{99}Tc, ^{107}Pd, ^{113}Cd, ^{115}In, ^{126}Sn, ^{129}I, ^{135,137}Cs, ^{142}Ce, ^{144}Nd, ^{151}Sm
Isotope Separation			

Fast Reactors and Closing Nuclear Fuel Cycle

ROSATOM

Fast RR

Fast Power Reactors

BN-1200
Decision made


21.12.21

BN-800 (Beloyarskaya NPP)
fully loaded with MOX


14.04.22

MBIR vessel delivered at constr.site
(Fast RR 150 MWt,
MOX, Pu-38%)
completed 2028


EU Taxonomy
accelerating sustainable investments

Complementary Climate Delegated Act
on certain nuclear and gas activities

- ✓ Research, development and deployment of advanced technologies ("Generation IV") that minimise waste and improve safety standards
- ✓ New nuclear plant projects with existing technologies for energy generation of electricity or heat ("Generation III+") (until 2045)
- ✓ Upgrades and modifications of existing nuclear plants for lifetime extension purposes (until 2040)


#FR22

International Conference on
FAST REACTORS AND RELATED FUEL CYCLES:
Sustainable Clean Energy for the Future

IAEA

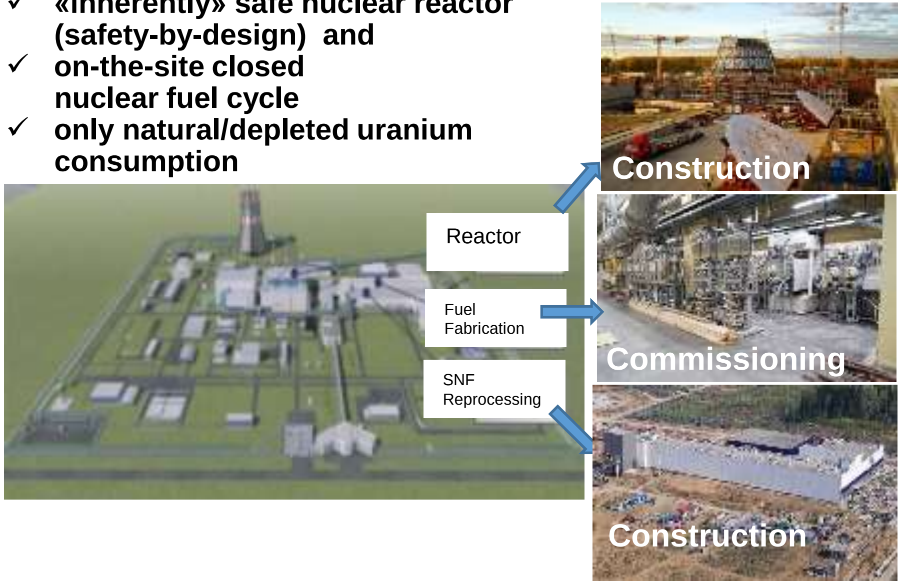
FR22 recommended to establish the Agency wide FR& FC Platform

“PRORYV” – Project: Way to Green Circular Economy

“Proriv” in Rus – “breakthrough”/ “way to the future”

General layout: **Current status:** **Start-up:**

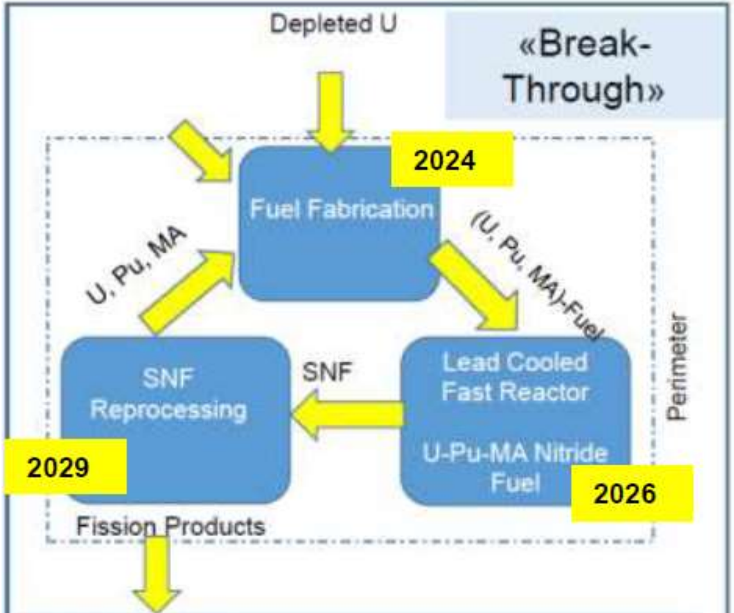
Demonstrating the feasibility of an
- ✓ **«inherently» safe nuclear reactor (safety-by-design) and**
- ✓ **on-the-site closed nuclear fuel cycle**
- ✓ **only natural/depleted uranium consumption**



2026

2024

2029



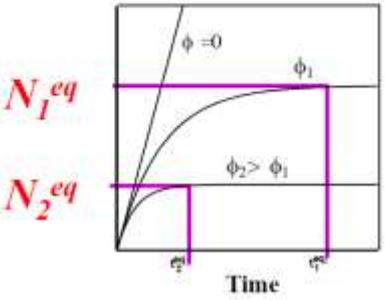
No U enrichment;
No Separated Pu;
Closing Fuel Cycle for a single NPP;
Localization of Nuclear Energy System on a single site;
Radiological Balance
(radioactivity of U consumed = radioactivity of disposed Fission Products)

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**

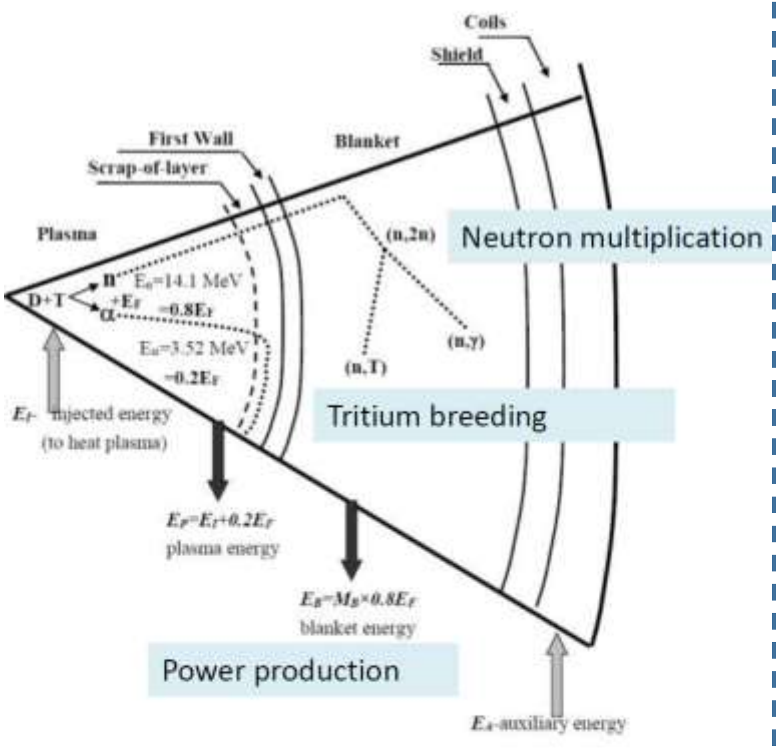


Nuclide	Half-life (yr)	Effective half-life (yr)		Time to approach equilibrium (yr)**	
		Fast Spectrum*	Thermal Spectrum*	Fast Spectrum	Thermal Spectrum
^{79}Se	6.5×10^{4}	7.3×10^{2}	2.1×10^{3}	2.41×10^{3}	7.07×10^{3}
^{90}Sr	**29**	**29**	**29**	**≈100**	**≈100**
^{93}Zr	1.5×10^{6}	730	790	2.44×10^{3}	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.

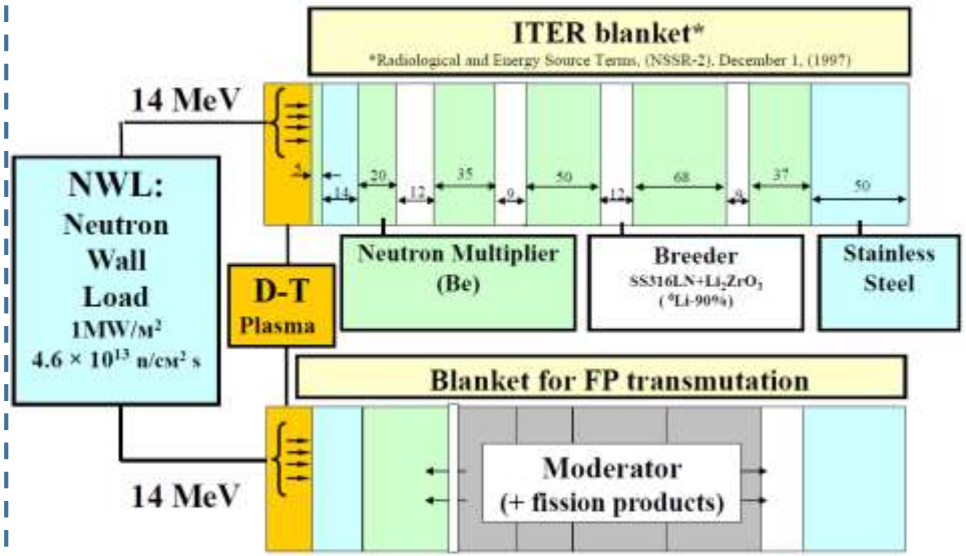
FNS Blanket Configurations



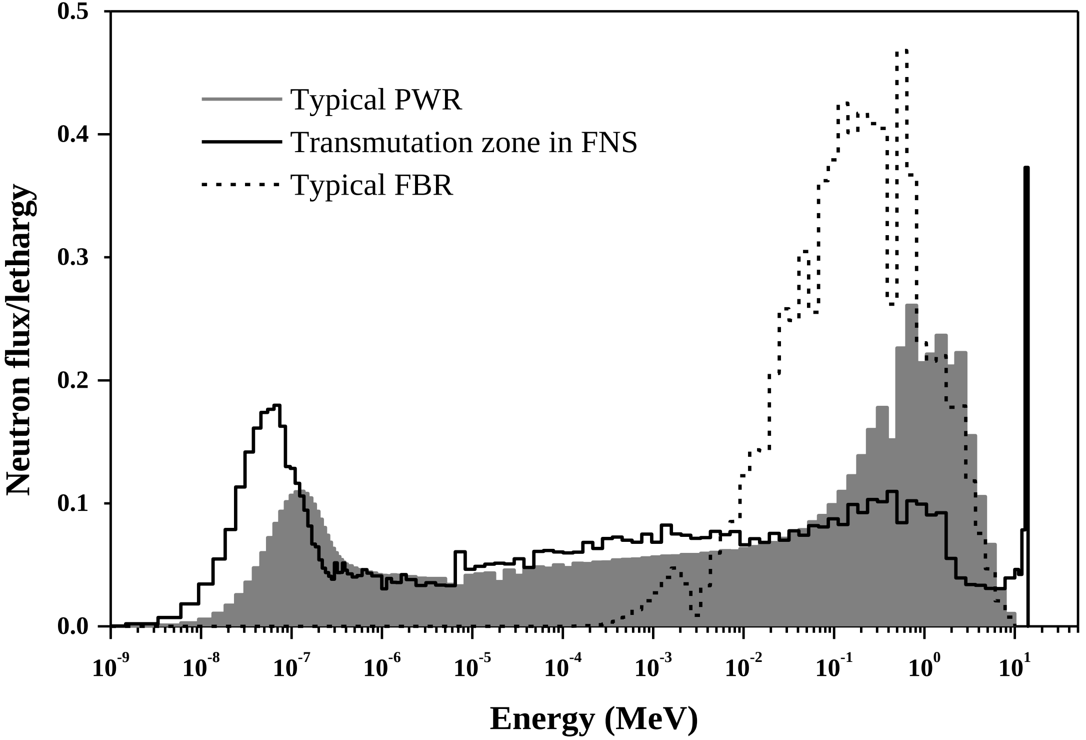
Neutron multiplication

Tritium breeding

Power production

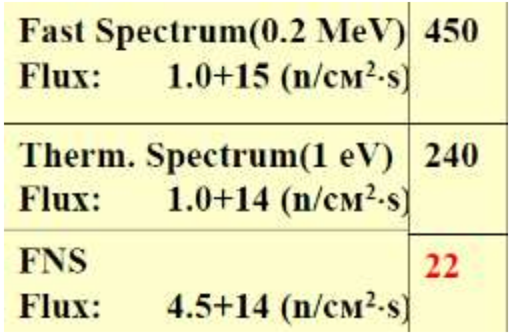


Elemental Cesium Transmutation



Neutron Balance

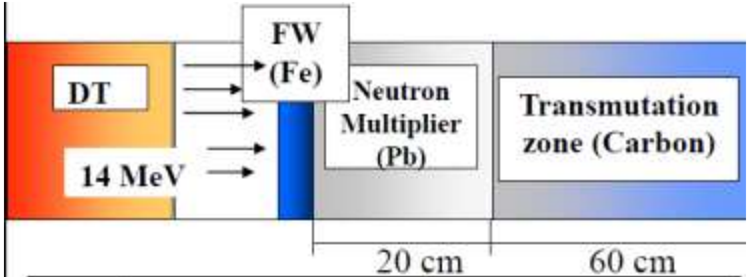
Mean life-time of Cs-135

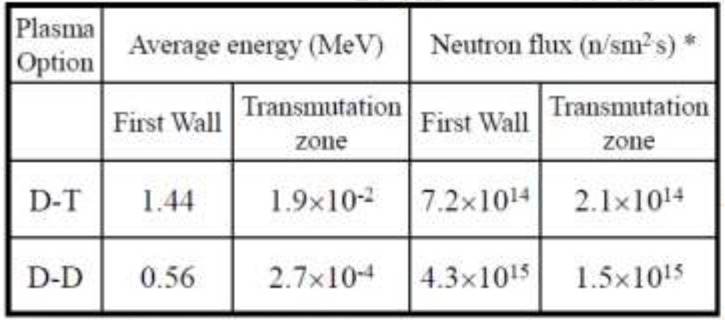


Fast Spectrum(0.2 MeV) Flux: 1.0+15 (n/см^2·s)	450
Therm. Spectrum(1 eV) Flux: 1.0+14 (n/см^2·s)	240
FNS Flux: 4.5+14 (n/см^2·s)	22

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

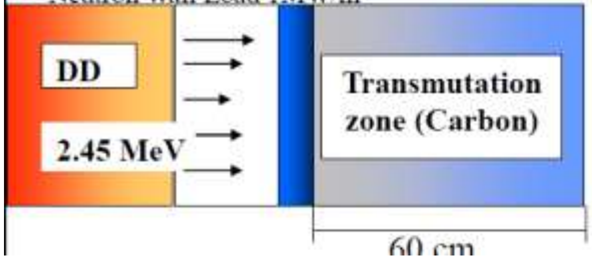
Specifics of FNS Neutronics



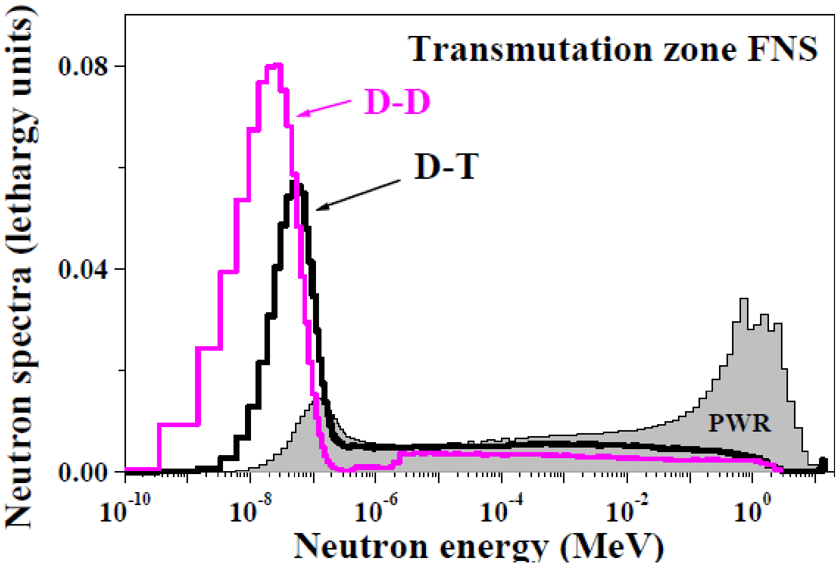


Plasma Option	Average energy (MeV)		Neutron flux ($n/sm^2 s$) *	
	First Wall	Transmutation zone	First Wall	Transmutation zone
D-T	1.44	1.9×10^{-2}	7.2×10^{14}	2.1×10^{14}
D-D	0.56	2.7×10^{-4}	4.3×10^{15}	1.5×10^{15}

* Neutron Wall Load $1 MW/m^2$



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))

Thank you for your attention

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13.12.2022

Competitiveness of nuclear power compared to alternative generation in the world (current situation)

Source: iea NEA

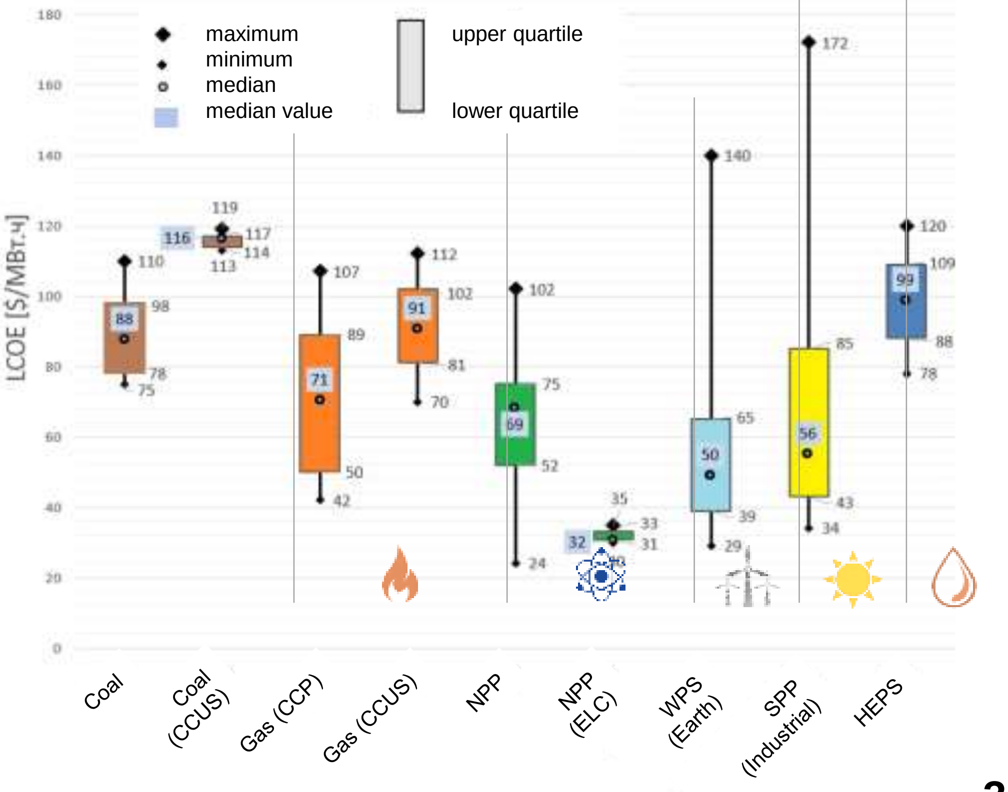
ROSATOM

An analysis was made of relevant foreign materials on the competitiveness of generation sources in comparison with nuclear energy based on data from 24 countries

Main conclusions:

- ❑ Low-CO2 power generation technologies, including nuclear power generation, are becoming more LCOE-efficient than fossil fuels
- ❑ The LCOE for new NPPs is gradually declining from $80/MWh to the current $69/MWh
- ❑ The LCOE index for extended life nuclear power plants is at the level of $30-35/MWh, i.e. this is the lowest among both low-carbon and traditional sources

Energy Technology LCOE (d=7%)

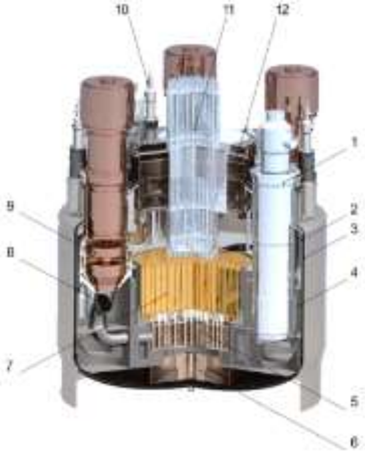


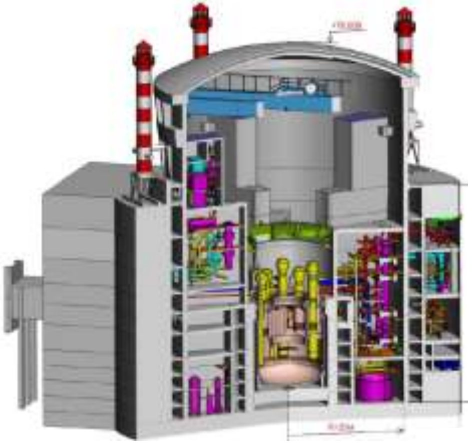
CCUS - carbon capture, utilization and storage

BN-1200 is the world's first commercial fast reactor

BN-1200M: current state

- ✓ The general concept has a reference, the technical design materials have been developed (end of 2021)
- ✓ Full or extended reproduction of fuel, afterburning MA
- ✓ Availability factor - 0.9
- ✓ The probability of severe damage to the core – 5x10-7 1/year
- ✓ Innovative elements are substantiated, computer programs are certified for innovative solutions, and regulatory documentation is being developed
- ✓ The power unit (feasibility study) is being optimized, while ensuring competitiveness - construction until ~ 2030

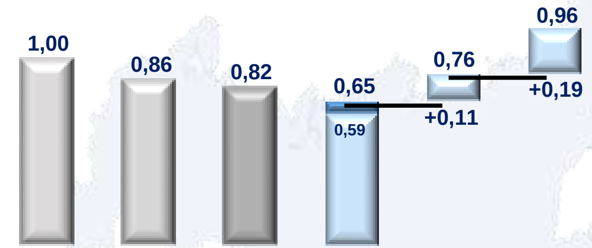




Economics of fast reactors

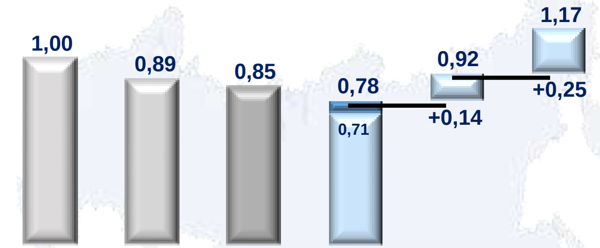
LCOE Energy Technologies, cent/kWh

discount rate 8%

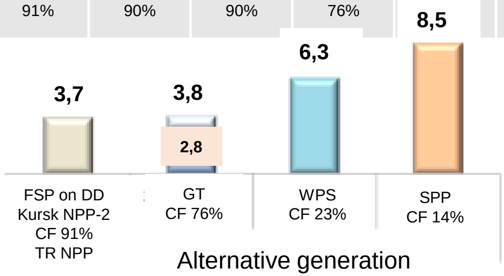


	FSP on DD Kursk NPP-2	Risk-Based FSP	Risk-Based FSP	The best FSPs for RF conditions	"Export parity" of gas prices	Payment for GHG emissions
	VVER-TOI	BN-1200M	BR-1200	GT	GT	GT
Capacity factor %	91%	90%	90%	76%	76%	76%

discount rate 5%



	FSP on DD Kursk NPP-2	Risk-Based FSP	Risk-Based FSP	The best FSPs for RF conditions	"Export parity" of gas prices	Payment for GHG emissions
	ВВЭР-TOI	BN-1200M	BR-1200	GT	GT	GT
	91%	90%	90%	76%		76%

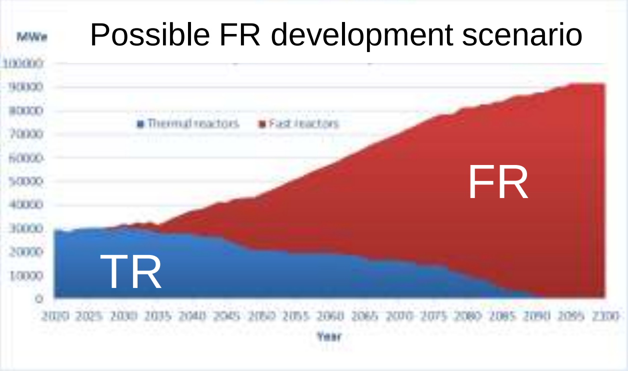


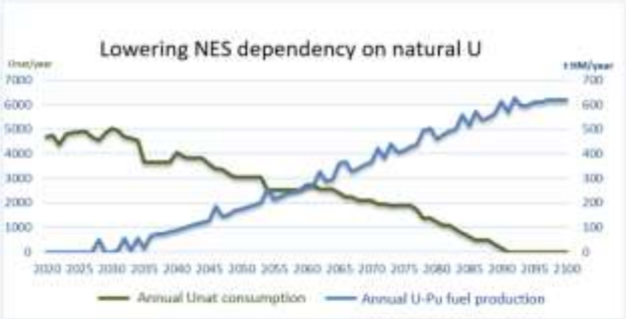
- ✓ **NPPs with FR and CNFC ensure the fulfillment of competitiveness requirements in relation to NPPs with TR**
- ✓ **NPPs with FR and CNFC have the potential to improve competitiveness with serial construction and development of two-component nuclear power**

What is a two-component NES

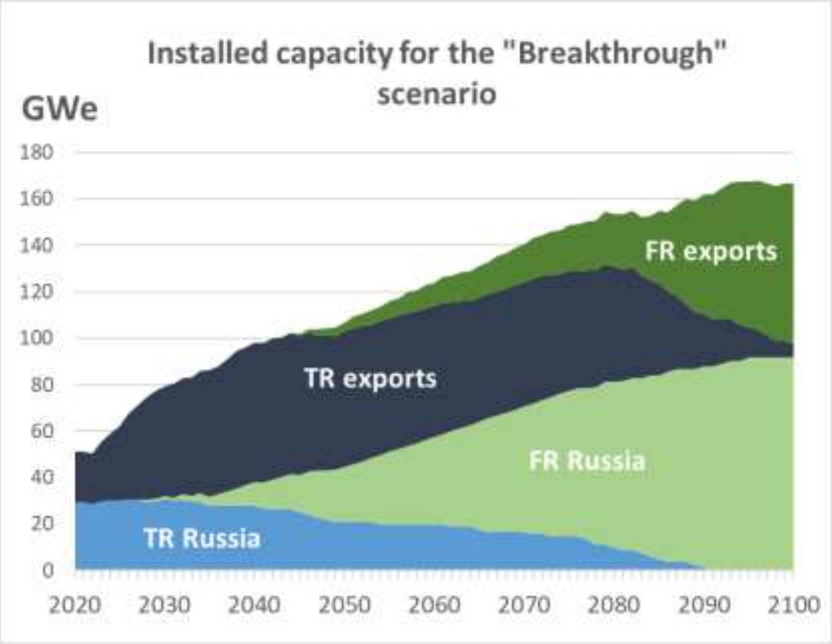
An optimal scenario for transitioning to a fully closed nuclear fuel cycle:

- ✓ Entire reactor fleet consisting of FR by the end of the century;
- ✓ Elimination of all thermal reactor SNF and stockpiled Pu in the FR cycle;
- ✓ All MA (from thermal reactor SNF) are recycled in FRs without including them in radioactive waste destined to final disposal;
- ✓ Fuel supply requirements are met for large-scale NES without applying blankets and high BR values;
- ✓ Fuel regeneration is concentrated in the core and facilitates FR safety along with MA transmutation.

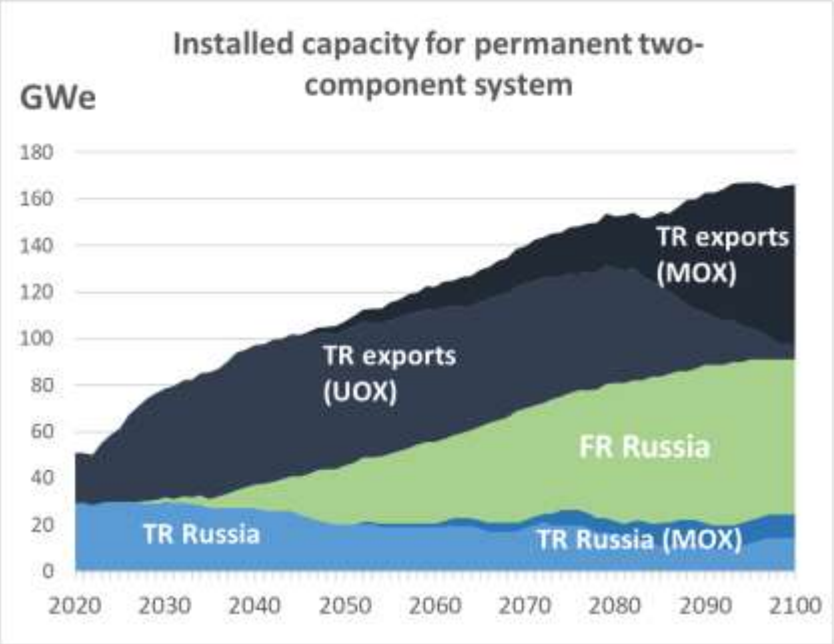




Fast reactor deployment strategies and their impact on the nuclear industrial complex in Russia – initial proposal for STEP FORWARD



FR breeding ratio ~1



FR = Pu breeders