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Fast Reactors and Nuclear Nonproliferation

E.N. Avrorin[a] and A.N. Chebeskov[b]

a) Russian Federal Nuclear Center - Zababakhin Institute of Applied Physics, Snezhinsk, Russia

b) State Scientific Center of the Russian Federation Institute for Physics and Power Engineering named after A.I. Leypunsky, Obninsk, Russia, e-mail: chebes@ippe.ru

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1. Introduction

"Peaceful power from atomic energy is no dream of the future. That capability, already proved, is here now – today".
«Атом должен быть рабочим, а не солдатом»

- About 60 years of peaceful use of nuclear energy.
- Large quantities of nuclear materials in NFC.
- Main nuclear technologies were born in weapons activity.
- Awaiting increase of number of newcomers throughout the globe.
- Possible temptation to use nuclear technologies and materials for another applications.
- Increase of proliferation risk.
- Calls for termination of NP to prevent clandestine activity under cover of NP.
- Use NP for NW is very long and expensive way.
- Nuclear nonproliferation is multilateral problem.
- State nuclear status: established NW states, de facto NW states, states possessing key NT, states developing or planning use of NE.
- Theft of NM and nuclear terrorism.

- Fast reactors and their fuel cycles.
- **President Ford 1976 Statement on Nuclear Policy, Nuclear Nonproliferation Act of President Carter Administration in 1978 started creating bad image of FRs.**
- Technological barriers and Institutional measures – may be applied for FRs as well.
- **What is the reason that countries try to develop nuclear weapons?**

"Countries try to develop nuclear weapons because they sometimes feel insecure, they sometimes feel threatened and they sometimes feel that nuclear weapons will bring some power and prestige". The IAEA Director General Mohamed ElBaradei told a news conference at the Japan National Press Club. "We need to work on all these motivations", ElBaradei said, adding that sanctions were not a long-term remedy to prevent nuclear proliferation. Tokyo, Japan, November 30, 2006

- **To reduce or eliminate stimuli in acquiring NWs.**
- To have a comprehensive set of requirements for countries developing nuclear power, which would be free of political preferences.
- It is necessary to develop both incentives for strict adherence to these requirements as well as penalties for their violation.

2. Nuclear materials

№	Isotope Half-life, year	Half-life, year	Neutron background, n/sec-kg	Decay heat, W/kg	Bare critical mass, кg	Activity, Ci/кg
1.	U-232	68.9	$4.0 \cdot 10^{-3}$	$7.2 \cdot 10^{2}$	~5	$2.2 \cdot 10^{4}$
2.	U-233	$1.6 \cdot 10^{5}$	1.2	0.3	16	9.6
3.	U-234	$2.5 \cdot 10^{5}$	7,2	0.2	~40	6.2
4.	U-235	$7.0 \cdot 10^{8}$	0.4	$6.0 \cdot 10^{-5}$	50	$2.2 \cdot 10^{-3}$
5.	U-236	$2.3 \cdot 10^{7}$	4.1	$1.8 \cdot 10^{-3}$	~170	$6.5 \cdot 10^{-2}$
6.	U-238	$4.5 \cdot 10^{9}$	10.8	$8.5 \cdot 10^{-6}$	-	$3.4 \cdot 10^{-4}$
7.	Pu-238	87.7	$2.7 \cdot 10^{6}$	**$5.7 \cdot 10^{2}$**	10	$1.7 \cdot 10^{4}$
8.	Pu-239	$2.4 \cdot 10^{4}$	$2.0 \cdot 10^{1}$	2.0	10	$6.2 \cdot 10^{1}$
9.	Pu-240	$6.6 \cdot 10^{3}$	**$1.0 \cdot 10^{6}$**	7.1	36	$2.3 \cdot 10^{2}$
10.	Pu-241	14.4	2.4	$1.3 \cdot 10^{2}$	13	$1.0 \cdot 10^{5}$
11.	Pu-242	$3.7 \cdot 10^{5}$	$1.8 \cdot 10^{6}$	0.1	92	4.0

Fissile materials of a NFC (source materials) - additional processing – direct- use-materials for NW

Chain fission reaction - not rather big critical mass.

High-enriched uranium and plutonium – differences

- **HEU is most attractive for nuclear weapons:**
  low neutron emissions - simple design of gun type: no testing.

- The development of a NW based on HEU would apparently be the most accessible for non-governmental criminal and terrorist groups.

- **Plutonium – implosion type, reactor-grade or civil plutonium…**

Properties of FMs to support sustaining uncontrolled chain nuclear reaction (E = 1 MeV)

$C = (\sigma_{sc} + \sigma_f \cdot n)/\sigma_t$, $\Phi(t) = \Phi_0 \cdot e^{\alpha t}$ $\alpha = (c-1)/\tau = (c-1) \cdot v/\lambda_t$

№	Isotope	C	σ_t, barn	λ_t, cm	γ, g/см^3	α, 1/мсsек	t_2, nsек
1.	U-233	1.43	6.5	3.15	18.9	273	**2.54**
2.	U-235	1.27	6.8	3.04	18.9	178	**3.90**
3.	Pu-239	1.40	7.9	2.54	19.8	315	**2.20**

3. Start-up and operation of plutonium-fuelled fast reactors.

- E. Fermi's and A. Leypunsky's dreams
- Start-up on Pu bred in thermal reactors
- No need in enrichment technology

	Fuel burn-up	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
PWR	33	1.6	56.5	23.8	12.8	5.4
	60	3.8	51.8	23.0	14.2	7.2
	100	7.8	47.0	21.7	14.7	8.8
MAGNOX	5	~0	68.5	25.0	5.3	1.2
CANDU	7.5	~0	66.5	26,5	5.5	1.5
WPu		0.012	93.8	**5.8**	0.35	0.022

Evolution of Pu isotopic composition in fast reactors

Pu-239 / Pu-240 / Pu-241 / Pu-242, %		Equilibrium Pu after many recycles Pu-239 / Pu-240 / Pu-241 / Pu-242
Loaded Pu in fresh fuel	Unloaded Pu in used fuel	
100 / 0 / 0 / 0	89,2 / 10,5 / 0,3 / 0,02	59,3 /31,4 / 5,7 / 3,6
60 /25 / 10,9 / 4,1	58,7 / 28,4 / 8,1 / 4,8	49,1 / 35,9 / 7,9 /7,1
55,0 / 20,8 / 17,8 / 5,9	57,5 / 24,3 / 11,1 / 7,1	53,2 / 33,0 / 7,3 / 6,5
43,2 / 38,8 / 10,3 / 7,7	43,8 / 38,8 / 9,2 / 8,2	45,5 / 37,9 / 7,9 / 8,7
41 / 40 / 8 / 11	4I / 40 / 8 / 11	4I / 40 / 8 / 11

- Pu irradiated in fast reactor will contain large amounts of even isotopes.
- WPu excess to defence needs will be utilized in BN-800 fast reactor:
  - to satisfy “spent fuel standard”:
  - **Pu-240/Pu-239 more than 0.1**
  - radioactivity level of 1 Sv/h during 30 years at 1 m distance
- Blankets of fast reactors : 96% Pu-239, ~4% Pu-240.
- Refusal of blankets in fast reactors:
  - eliminates production of weapons-like plutonium
  - leads to a decrease in the reactor breeding ratio, and loss of additional plutonium which could be used to speed the expansion of fast nuclear power.

Along with institutional measures, the following solutions of this problem are possible:

- **Joint management and reprocessing** of spent fuel S/As from the core and irradiated blanket S/As;
- **Excluding separation of pure Pu** when reprocessing spent fuel and blanket S/As, mix of 50 % U and 50 % Pu in separated material streams;
- Elimination of breeding blankets in fast reactors or use blankets for production of other isotopes besides: U-233, etc.;
- **Organization of international centres for rendering services in the nuclear fuel cycle;**
- Various options of denaturation of Pu proposed in recent years are counterproductive.

4. Start-up of fast reactors using enriched uranium fuel.

- Independence of thermal reactors;
- Transition to U-Pu fuel using own bred Pu:
- Need in enrichment technology
- Need in separation technology
- Enriched U and high-grade Pu during transition phase
- High-grade Pu in the core and in blankets

Pu isotope	After the 1st micro-campaign, %	After full campaign, %
Pu-238	0.02	0.11
Pu-239	98.73	95.47
Pu-240	**1.24**	**4.28**
Pu-241	0.01	0.14
Pu-242	0	0.003

5. Uranium enrichment and nuclear nonproliferation.

- U in contrast to Pu **doesn’t have strong enough inherent features of resistance to proliferation** (heat release, neutron background, radioactivity).

- Possible to manufacture **gun-type NED using HEU**, and almost **impossible to do the same using plutonium**.

- It seems, any state or group is able to manufacture gun-type NED if having **ordnance technology in hands (and of course HEU)**.

- Implosion-type NED needs more sophisticated technology.

- **Achievements in centrifuge technology:** small sizes, comparably small consumption of water and electricity, possibility to arrange clandestine HEU production.

Uranium enrichment technology is posing more risk of proliferation than plutonium separation

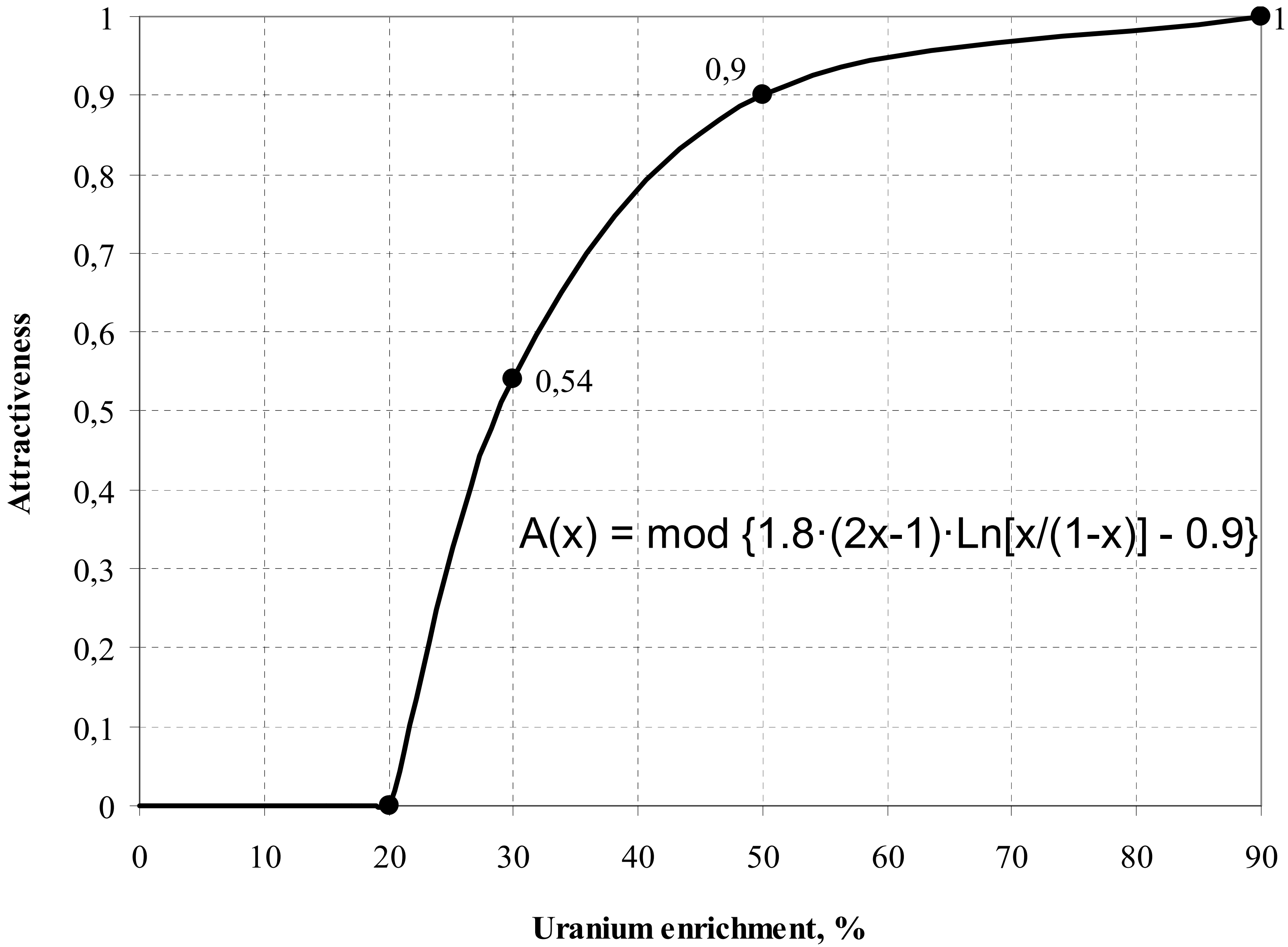
Proposed classification of high enriched uranium

Parameter	Highly attractive	Attractive	Low attractive	Non-attractive
Enrichment, % U^{235}	$50<X\leq 90$	$30<X\leq 50$	$20<X\leq 30$	$X\leq 20$
Quantity of HEU, kg	$25\leq M_{NED}<50$	$50\leq M_{NED}<150$	$150\leq M_{NED}<400$	$400\leq M_{NED}$
Effective material volume in NED, l	1.3 - 2.6	2.6 - 8.1	8.1 - 21.5	≥21.5
Amount of SWU, $x10^3$	$5.7_{90\%}$ - $6.1_{50\%}$	$6.1_{50\%}$ - $10.2_{30\%}$	$10.2_{30\%}$ - $18.2_{20\%}$	≥18.2
Quantity of nat. U, t	$4.4_{90\%}$ - $4.9_{50\%}$	$4.9_{50\%}$ - $8.7_{30\%}$	$8.7_{30\%}$ - $15.5_{20\%}$	$\geq 15.5_{20\%}$
Electricity, kW-h, $x10^5$	3.4 – 3.7	3.7 – 6.1	6.1 – 10.9	≥10.9
Relative time needed for 1 NED	1.0-1.1	1.1 – 1.8	1.8 – 3.2	≥3.2

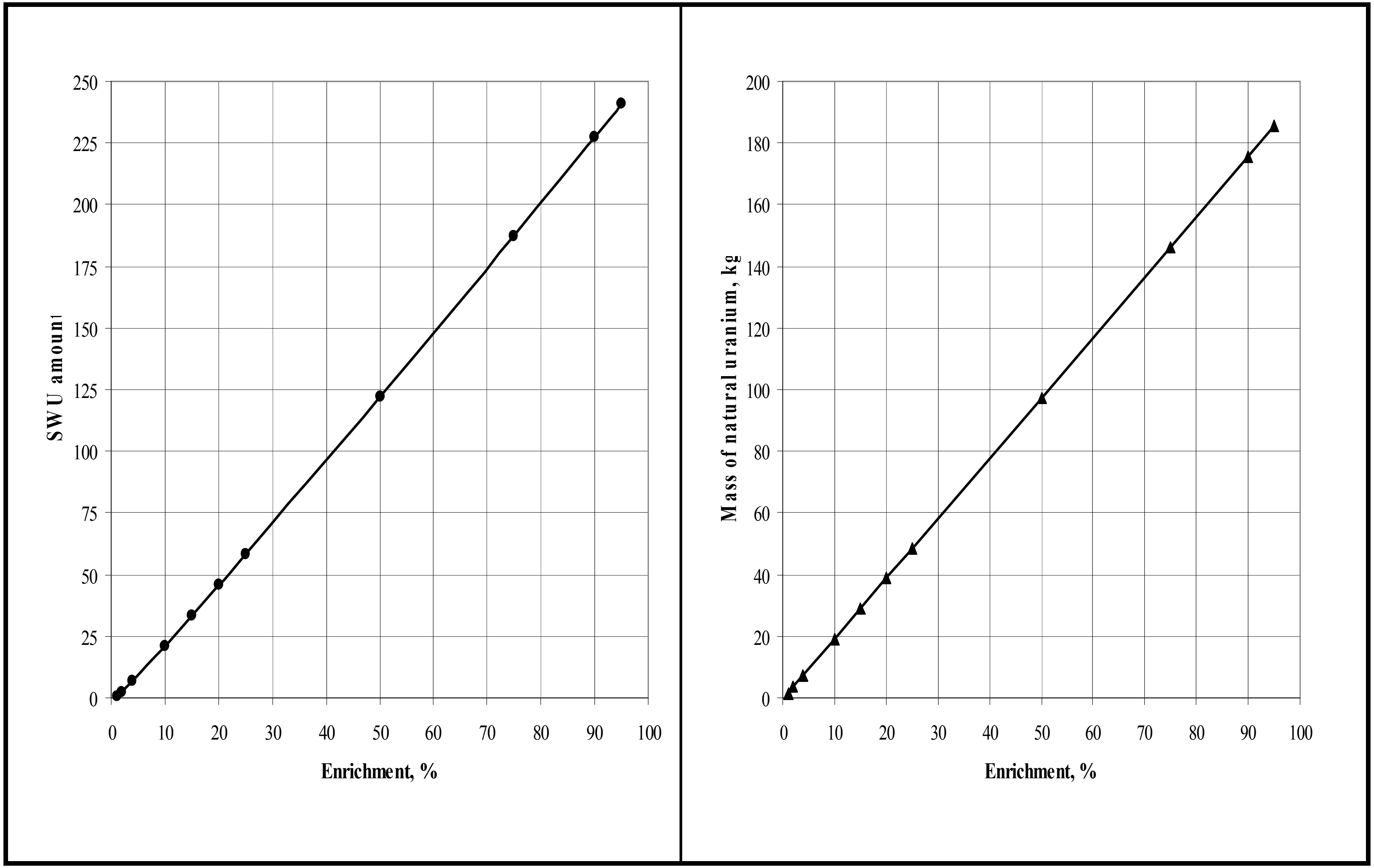
State-proliferator having enrichment technology will try to reach **as high of uranium enrichment as possible** due to the following reasons:

- needs **comparably small amount of fissile material** to manufacture "faster" device, that
- leads, as a rule, to a bigger energy yield during explosion;
- needs **a smaller quantity of an initial material (natural uranium)**;
- needs the **less number of SWU**;
- needs **less quantity of electric energy**;
- needs **less time.**

Attractiveness of HEU versus its enrichment
(based on Peierls-Dirac formula on separation potential or value function)



Numbers of SWUs (left) and mass of natural uranium (right) needed to produce 1 kg of enriched uranium vs its enrichment



Amount of feed material and number of SWU needed for the production 25 kg of HEU

	Feed material			
	Natural U	Uranium fuel of TR	Uranium fuel of FR	
	0.711%	4%	15%	20%
Mass of feed material	4.4 t	590 kg	150 kg	110 kg
Number of SWU	$5.7 \cdot 10^3$	$1.8 \cdot 10^3$	750	500

When using fuel of nuclear power reactors as feed materials, there will be enough feed material **from about two fuel S/As to produce HEU for one SQ.**

Separate Work: $F = P + W$,

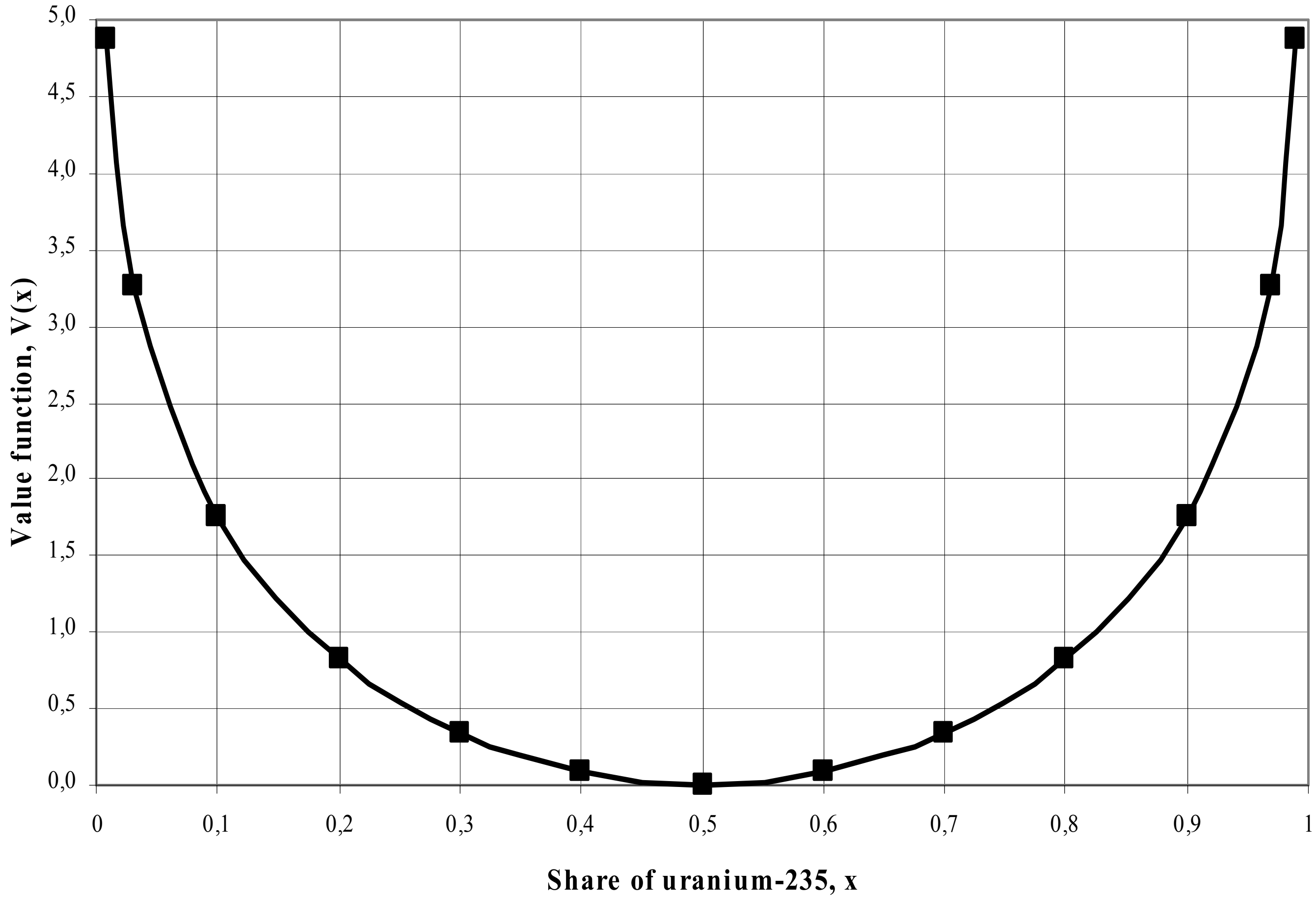
$F \cdot x_F = P \cdot x_p + W \cdot x_W$,

$F = P \cdot (x_P - x_W)/(x_F - x_W)$

$A = P \cdot V(x_P) + W \cdot V(x_W) - F \cdot V(x_F)$

Peierls-Dirac formula for separation potential

$$V(x) = (2x - 1)\cdot\ln[x/(1-x)]$$



6. Possible scenarios of fast nuclear power development.

- **“Conceptual items of strategy for nuclear power development in Russia in 21st century”:**
  - To meet all safety requirements, achieving confidence of the society, improvement of total fuel and energy balance - strategy of large-scale development,
  - Average annual increase in electricity demand 2.3% by 2030 and 0.5% by 2100, 70 % by nuclear in 2100
  - Two scenarios: **scenario A – two-component NP: Pu for FRs, U for TRs, share of FRs depends on Pu availability,**
  - **Scenario B – only FRs beyond 2030: 5-6 units/year of 1200 MW(e) between 2030-2070 with the use of Pu and U**
- Accelerated deployment of FRs with Pu and U fuel allows not only **provide the maximum contribution of nuclear power** in the general energy balance of the country, but also **finally to solve a problem of the fuel resources** with transition to self-sufficiency on fuel and **the termination of natural U consumption**.
- Fuel component of the electric power generation cost in closed NFC of FRs is economically more favorable, than open NFC of LWRs.

7. “Reminiscence of the Future”– INFCE (Oct 1977 – Feb 1980)

- NP is playing an increasingly important part in meeting the world's energy requirements
- **Fast breeder reactors could in the long term play a major role**
- The peaceful use of nuclear energy is neither the easiest nor more economic method of manufacturing nuclear weapons
- The risks of proliferation inherent in the various cycles cannot be compared in an abstract manner but depend on a number of specific factors… **there are neither cycles that are totally free from risks nor cycles that are per se incompatible with the objectives on nonproliferation**
- All measures to prevent proliferation should be used, **but these measures should not hamper development of nuclear power for peaceful purposes**
- Operation of nuclear reactors inevitably connects with Pu production, the task is not to avoid this production but how to manage well with this material
- **Fuel cycle of FRs is no more risky then fuel cycle of TRs with U-Pu fuel**
- **Institutional measures**: IntPuStorage, IntSNFManagement, limitation of sensitive installations, design and construction of these installation on a multinational basis
- **Technical measures:** replace HEU with LEU in research reactors, eliminate pure forms of NMs, physical barriers
- **Keeping open the option of recycling Pu in thermal and fast reactors; this in turn implies the reprocessing of irradiated fuel (USA Nuclear Nonproliferation ACT, March, 1978).**

8. Conclusion remarks

1. Fast reactor start-up with U-Pu fuel:
   - dependent on thermal reactors,
   - no needs in U enrichment,
   - needs in SNF reprocessing,
   - Pu is a little suitable for NED,
   - practically impossible gun-type NED,
   - difficulties for implosion-type NED: necessary tests, advanced technologies, etc.
   - Pu in blankets is similar to WPu by isotopic composition,
   - Use of blanket for production isotopes (e.g. ^{233}U)
   - Combined reprocessing of SNF: altogether blanket and core,
   - Blanket elimination: decrease in Pu production
   - No pure Pu separation

2. Fast reactor start-up with U fuel:

- Needs in both U enrichment and SNF reprocessing,
- Independent of thermal reactors,
- Good Pu bred in the core let alone blankets,
- NED of simple gun-type design,
- Increase of needs in SWU,
- Increased demands in U supply.

3. Fast reactors for export:

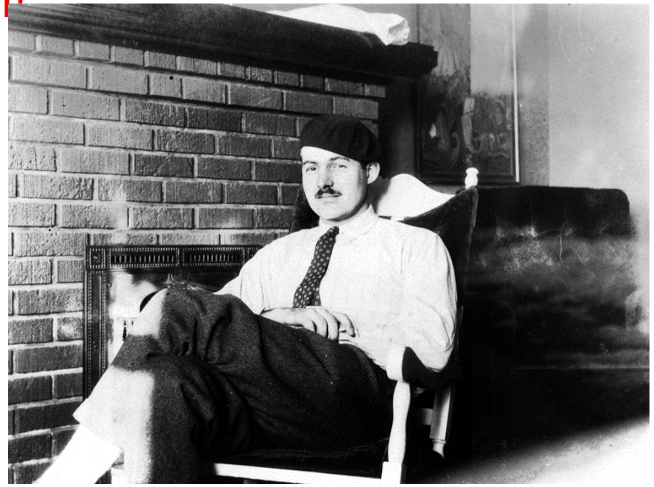
- Uranium shortage,
- To replace thermal reactors in future,
- No blankets (depends on the country, though),
- Fuel supply and SNF take back,
- International centers for rendering services of NFC.

Time has come to remove from FRs and their NFC the label unfairly identifying them as the most dangerous installations of nuclear power from the standpoint of being a proliferation problem.

Thank you very much for your kind attention!

Thanks a lot to the IAEA for the FR13 Conference!

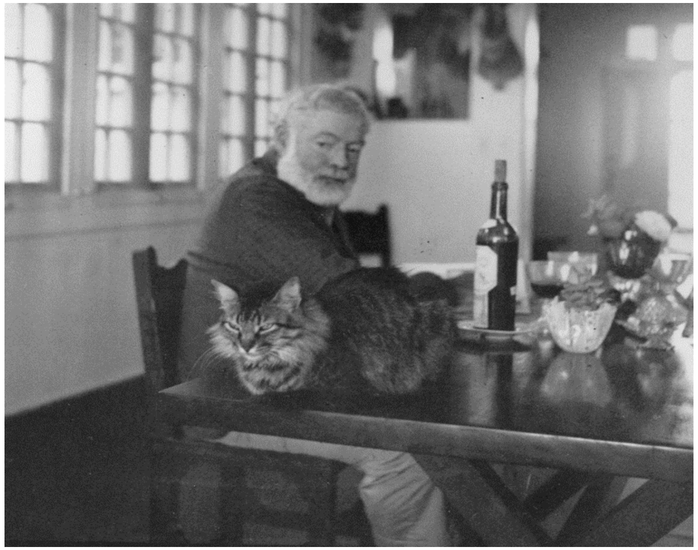
Special thanks to Paris-city and its people!



Paris, 1924

"If you are lucky enough to have lived in Paris as a young man, then wherever you go for the rest of your life, it stays with you, **for Paris is a moveable feast."**

Ernest Hemingway



Last photo, 1961