Large-Scale Future Nuclear Power and the Problem of RAW Handling

PDIPE-NIKIET:

V.V. Orlov, I.Kh. Ganev, V.V. Naumov, L.V. Tochenij
A.V. Lopatkin

LANU

1. Social acceptance
   - smokelessness, no CO_2
   - no rise of temperature
   - no "greenhouse" effect
   - high-energy potential
   - less long-distance transport problems
   - no sense for power increase

2. The 2nd Nuclear Era

- free market
- new energy-conserving industries
- large-scale NP (≥20%30%)
- there is potential for it

3. Safety NP

- inherent safety under severe accidents
- acceptable economy
- minimum of reactor types

fast reactor

- lead-cooled fast reactor

4. The RAW handling Phylosophy

- to develop the Normales for leakages (coolant plus corrosion and FP, radioactive gases, aerosoles ets.)

  decontamination

  evaporation, burning methods for RA materials
- compacting RAW for storage
- choice of NPP types (low-activation
- choice of fuel types
- adoption the Principal of Radio-Equivalent RAW Disposal

5. The PRINCIPLE of Radio-EQUIVALENT RAW DISPOSAL

The nat. U activity

$$A^{U_{nat}} = 5.2\ Ci/t$$

U-family $\to \alpha$

FP, SM $\to \beta, \gamma$

Radio-EQUIVALENCE:

$$A^{U_{nat}}_{RE} = A^{U_{nat}} \cdot \overline{K}_R$$

$$\overline{K}_R^{-1} = \sum_j K_{Rj}^{-1} A_j \Big/ \sum_j A_j \qquad K_{Rj} = \frac{LC_j}{LC_{U_{nat}}}$$

Equiv. mass $M^{Eq}_{U_{nat}} = \dfrac{A_{RAW}\,(Ci)}{A_{U_{nat}}\,(Ci/t)}$

Rad.-Eq. mass

$$M^{REq}_{U_{nat}} = \frac{M^{Eq}_{U_{nat}}}{K_R} = \frac{A_{RAW}}{5.2 \cdot K_R}$$

Rad.-Equiv. Balance (ORLOV' principle)

$$\sum_j M_j^{REq} \leq M^{out}_{U_{nat}} \qquad \frac{t}{GWe\,yr}$$

$$\sum_i \sum_k \sum_j W_i T_{ik} L_{ikj} M_{ijk}^{REq}(\tau_{ik}) \leq M^{out}_{U_{nat}}$$

i - NPP $\qquad \tau_{ik} = T^* - T_{ik}$

W_i - GWe

T^* - action time of NP

T_{ik} – 'K' life-time

j - nuclide

L_{ikj} - residual parts of RAW nuclides

Long-lived FP (^{235}U)

Nuclide	$T_{1/2}$, Yr	Y, %	m, kg/GWe	/4" Ci/GWe	K^{H_2O}	$M^{REq}_{U_{NAT}}$ t/GWey
^{79}Se	6.5+4	0.035	0.147	14.7	10	0.2
^{93}Zr	9.5+5	6.4	26.9	159.	667	0.032
^{99}Tc	3.13+5	6.3	26.5	642.2	133	0.65
^{107}Pd	7.+6	0.18	0.76	0.518	100	7-4
^{129}I	1.6+7	1.0	4.2	1.06	0.16	0.9
^{135}Cs	2.3+	6.4	26.9	45	91.7	0.07
Σ		20.	85.4	863	227	1.85

Middle-lived FP (^{235}U)

Nuclide	$T_{1/2}$ year	y, %	$\dot{m}$ kg/GWe·Y	$K^{Rad}_{H_2O}$	τ year	$\dot{A}$ Ci/GWe·Y	M^{REq} t/GWe·Yr
^{85}Kr	10.74	1.-3	5.46	(10)*	200	7.7	0.104
^{90}Sr	29.12	5.8	24.4	0.333	600	3.1	2.48
^{137}Cs	30.0	6.	25.2	12.5	400	313.8	6.76
^{155}Eu	496	0.031	0.13	167	60	20.2	0.02
^{151}Sm	90	0.45	1.89	317	200	2.3+4	13.85
^{126}Sn	76	9.-4	3.0-3	(10)*	200	34.6	0.66
Σ			57.1				23.9*

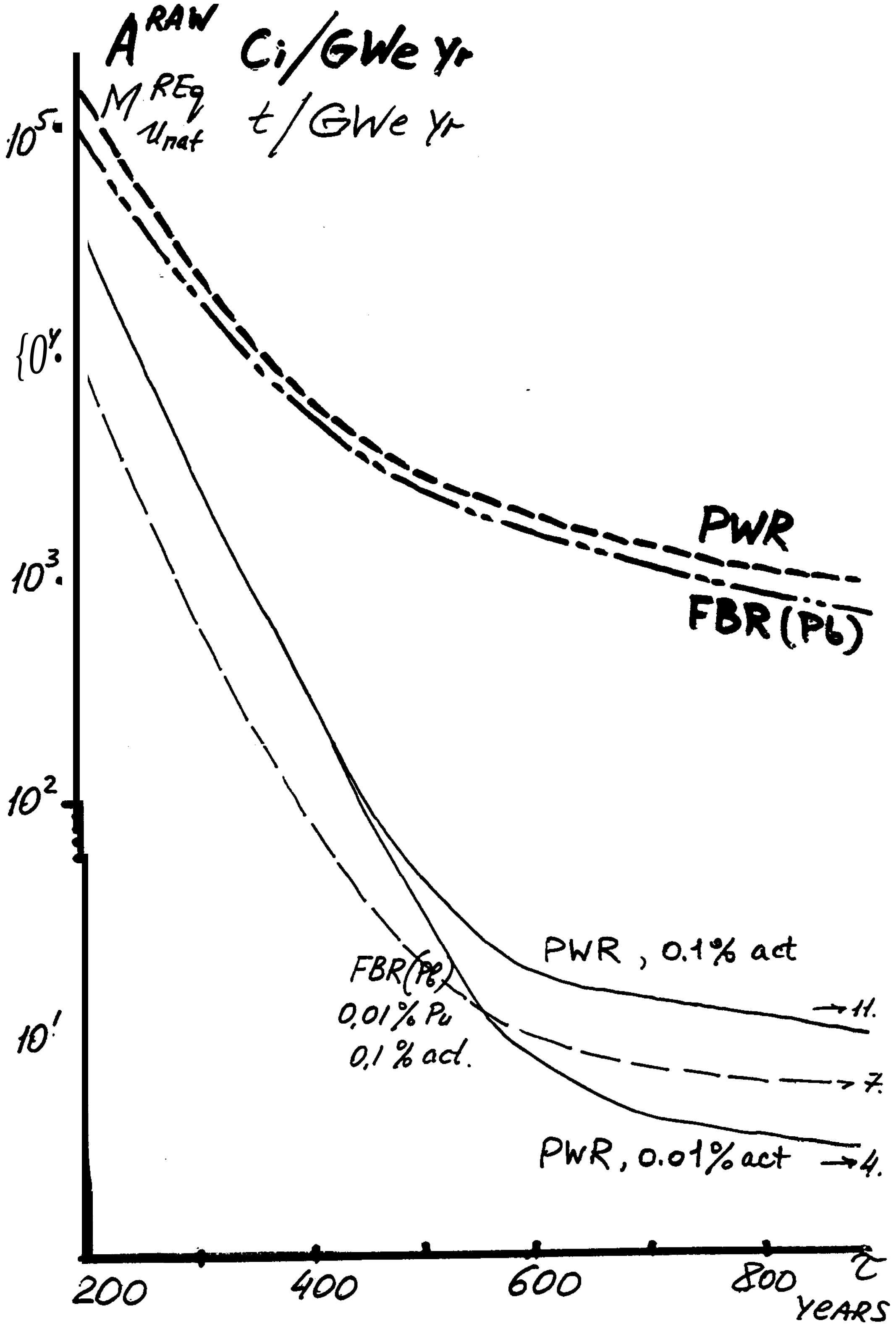
Structural materials

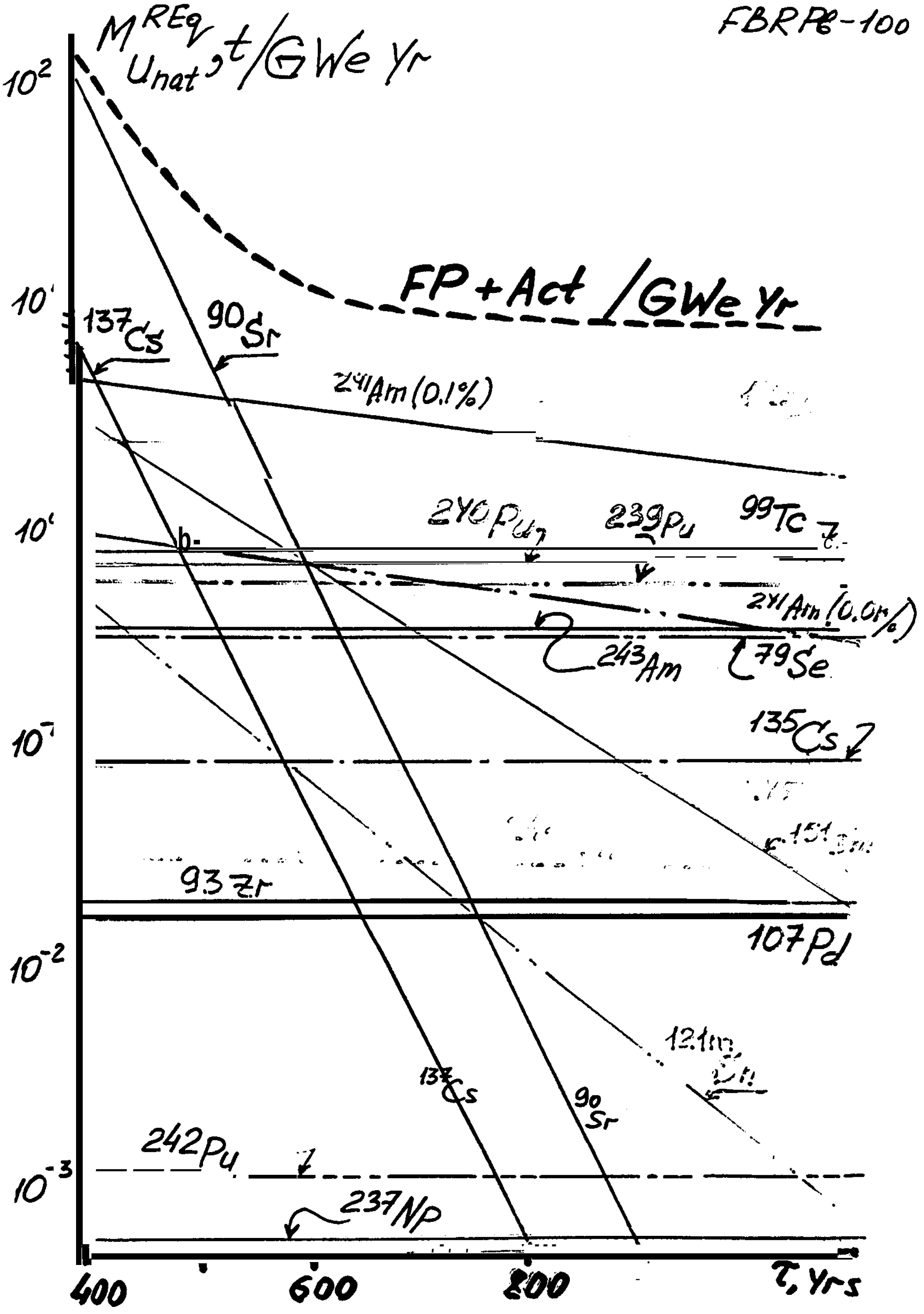
	PWR	$\Phi \sim 5.+12$ cm^{-2}c^{-1} SS - 100 t $\sim 5.+13$ cm^{-2}c^{-1} Zr 24 t				
Nuclide	$T_{1/2}$ year	ε_{i-1} %	τ year	A Ci/GWe Yr	K_{RAA}	m^{REq} t/GWe Yr
^{59}Ni	8.+4	67.8	600	215	167	0.28
^{63}Ni	92.	3.66	600	367	23.3	3.01
^{93}Zr	gin-5	17.1	0	3.4	667.	8.8-4
Σ			615			3.3

Residue Actinoids

Nuclid	$T_{1/2}$ YEAR	m kg/GWe·y	K^{H_2O}	A Ci/GWe·y	M^{REq} t/GWe Yr 0.1%	0.01%
^{237}Np	2.14+6	18.1	1.25	12.8	0.002	~0
^{241}Am	433	2.1	1.58	7.3+3	0.88	0.09
^{243}Am	7.37+3	2.4	1.83	480	0.05	~0
^{244}Cm	18.1	0.48	3.	3.9+4	2.49	0.25
^{239}Pu	2.44+4	154	1.83	9.5+3	1.	0.1
^{240}Pu	6.6+3	58.8	1.83	1.3+4	1.4	0.14
^{241}Pu	14.3	50.4	91.7	5.2+6	11→22	1.1→2.2
^{242}Pu	3.87+5	16.8	2	62.5	0.006	~0
Σ				5.3+6	16.8→ →27.5	1.7→ 2.8

$$\rightarrow \quad {}^{241}Pu \rightarrow {}^{241}Am \qquad M^{REq}(Am) = M^{REq}(Pu)\,\frac{T_{1/2\,Pu}}{T_{1/2\,Am}}\,\frac{K^{Pu}}{K^{Am}}$$


A RAW Ci/GWe yr
M REq Unat t/GWe yr
10⁵
10⁴
10³
10²
10¹
PWR
FBR(Pb)
PWR, 0.1% act
→11.
FBR(Pb)
0,01% Pu
0,1% act.
→7.
PWR, 0.01% act
→4.
200
400
600
800
τ
YEARS


$M^{REq}_{U_{nat}}$, t/GWe Yr
FBRPu-100
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
^{137}Cs
^{90}Sr
FP+Act /GWe Yr
^{241}Am (0.1%)
^{240}Pu
^{239}Pu
^{99}Tc
^{241}Am (0.01%)
^{243}Am
^{79}Se
^{135}Cs
^{151}Sm
^{93}Zr
^{107}Pd
^{121m}Sn
^{137}Cs
^{90}Sr
^{242}Pu
^{237}Np
400
600
800
τ, Yrs

For REq WD Priciple :

- change the initial part of fuel cycle
  (Th, Ac, Pa, Ra .... → to FBR)
- destruction and compacting of RAW
  (FP, structural metals, residue actinoids...)
- recovery of near-Pu (Np, Am, Cm ...)
  → to FBR burn-up
- controllable storage
- transmutation of actinoids to FP
  (FBR, Accelerators and so on.)

$\tilde{\Phi} = \ln 2 / \sigma_a \cdot \tilde{T}_{1/2}$ $\tilde{T}_{1/2} = 10$ yrs

	$\tilde{\Phi} / \Phi_{NOM}$		RBMK-1000	
Nuclide	Fuel channel		Grafite	
	Lib-1	Lib-2	Lib-1	Lib-2
^{79}Se	2,1		1.24	–
^{90}Sr	123	124	73.4	64.2
^{93}Zr	33,6	32.7	22.6	18.9
^{94}Nb	5.0	4.25	3.21	2.62
^{99}Tc	2.5	2.15	1.66	1.3
^{107}Pd	5.8	6.18	4.54	3.82
^{126}Sn	995	360	652	190
^{129}I	3.9	3.75	2.34	2.0
^{135}Cs	6.3	7.2	4.28	4.39
^{137}Cs	477	637	347	392
^{151}Sm	0,22		0.18	–

^{135}Cs ($T_{1/2} = 2.3\cdot10^{6}$ yr)

$t_0 = 0 \rightarrow$ I : ^{135}Cs - 100%

II: RBMK- ~1000

^{133}Cs 31.8%
^{134}Cs 1.7%
^{135}Cs - 34.9%
^{137}Cs 31.6%

(n,γ):	^{133}Cs	^{134}Cs	^{135}Cs	^{137}Cs
	71.6%	10.1%	18.1%	0.2%

t = 30 ef. yrs

Nuclides	I	II
^{133}Cs	1.9-7	40.9
^{134}Cs	1.9-3	5.9
^{135}Cs	623	292
^{137}Cs	7.3-2	158
^{133}Ba	2.9-7	2.6-3
^{134}Ba	2.2-2	172
^{135}Ba	1.5-2	13.6
^{136}Ba	373	159
^{137}Ba	3.8	144
^{138}Ba	2.6-1	16.8
^{137}La	3.5-14	4.9-12
^{138}La	5.3-9	6.1-7
^{139}La	8.4-4	7.9-2

$^{136}Cs \xrightarrow{13d} {}^{136}Ba$ $\Phi \sim 4\cdot10^{17}$

ITEP
\+ FEI
MPEI
IAE
INE
\- - - - - -

RDIPE - NIKIET

The Transmutation activity

Actinoids
Special Fast Reactors } I.Kh. Ganev
Controlled Storage } V.V. Naumov

LLFP
Thermal reactors } A.V. Lopatkin
Fast reactors } S.V. Kuznetsov
Fusion blanket } I.V. Zaiko
Acc - Driven blanket
Codes, data

BLC - code:

α, β^+, β^- decays
(n,f)
(n,γ)
(n,p)
(n,α)
(n,2n) … (n,7n)

burn-up, breeding
adjoint functions
sensitivity analisis
optimization

Library:

* JNDC - Nuclear Data Library of FP
JAERI - M, 1989
1990
\- Versions 2, 3

* AB Gusev et al. Goup sections of FP, 198

* Ju.N. Shubin (n,2n) cross sections estimates
\- FEI, Obninsk.

The upper estimates of transmutation (LLFP in the thermal and fast reactors)

__the 1st Stage__ - The calculations of LLFP and accompanied by stable nuclides in irradiated fuel.

Reactor - RBMK-1000

Burn-up 0-5-10-15-20 MW-d/kg

__Results:__

$^{127,128,129}I$, ^{129}Xe, $^{130,131,132}I+Xe$, $^{134,136}Xe$,

$^{133,135}Xe+Cs$, ^{134}Cs, ^{137}Cs, $^{134\div138}Ba$, $^{137,138}La$, $^{139}Ba+La$

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^{90}Sr : ^{85}Rb, ^{87}Rb, ^{84}Sr, $^{86}Rb+Sr$, ^{87}Sr, ^{88}Rb, ^{88}Sr, ^{90}Sr, ^{89}Y

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^{107}Pd : ^{104}Rh, $^{104\div110}Pd$ $^{107,109}Ag$

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^{79}Se, ^{81}Kr : $^{75\div82}Se$, $^{79,81}Br$, $^{80\div86}Kr$, $^{85,87}Rb$

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^{93}Zr, ^{94}Nb, ^{93}Mo, Tc : $^{90}Zr\div{}^{96}Zr$, $^{93,94}Nb$, $^{92-100}Mo$ $^{96\div99}Tc$

94?-/0//4

The LLFP contents in one year irradiated fuel (RBMK-1000)

Nuclides	δ, at%	M_{FP}, kg/yr
^{79}Se	9,0-4	0,165
^{81}Kr	7.4-10	1.4-7
^{90}Sr	8.7-2	18.0
^{93}Zr	08//	23.5
^{94}Nb	9,9-8	2,2-5
^{93}Mo	4.8-13	1.0-10
^{97}Tc	4.0-11	9.0-9
^{98}Tc	3.4-7	7,7-5
^{99}Tc	0,117	26.7
^{107}Pd	0.02 8	6.9
^{108}Ag	1.3-8	3.3-6
^{121}Sn	2.6-4	0. 07/
^{126}Sn	1.1-3	0,32
^{129}I	0. 0/9	5.55
^{135}Cs	0.14	43s
^{137}Cs	0,127	40.
^{137}La	1,7-8	5,6-6
^{146}Sm	3,2-12	1.1-9
^{151}Sm	8.4-3	2.91
^{157}Tb	1.3-12	4,6-10
^{158}Tb	1,8-12	6.5-10

Stage 2 $T^*_{1/2} = 10$ yrs $\Phi^* = \frac{\ln 2}{\sigma_d \cdot T^*_{1/2}}$

! We have no data!

^{81}Kr ^{93}Mo ^{97}Tc ^{98}Tc ^{121}Sn ^{137}La ^{146}Sm

^{149}Gd ^{150}Gd ^{157}Tb ^{158}Tb ^{108m}Ag

	Channel	Φ^*/Φ_{NOM} Graphite
^{79}Se	2.7 —	1.24 —
^{90}Sr	123 — 124	73.4 64.2
^{93}Zr	33,6 – 32,7	22.6 18.9
^{94}Nb	5.0 – 4.25	3.21 - 2.62
^{99}Tc	2.5 2.15	1.66 - 1.3
^{107}Pd	5.8 6.18	4.54 3.82
^{126}Sn	995 – 360	652 490
^{129}I	3.9 3.75	2.34 2.0
^{135}Cs	6.3 7.2	4.28 4.39
^{137}Cs	477 633	347 392
^{151}Sm	! 0.22 — (!)0,0008	0,18 0,0004

1. The increasing of Φ is nessesery. (ex. Sm)
2. The 'soft' spectrum is better
3. The nominal Φ ~ 12 – 45 yrs $T_{1/2}$
4. Cross-sections differ

Stage 3 RBMK-1000 3200 MWt $2.5 \cdot 10^{20}$ n/s

β% → to transmutation $M_{tr} = Q_n \cdot \beta \cdot A \cdot T/N_a = 13,1 \cdot \beta \cdot A \frac{kg}{yr}$

Nuclide	$M \frac{kg}{yr}$	β	$T_{tr}^{1/2}$, yrs	G, kg	Ci
^{79}Se	0,17	$1.6 \cdot 10^{-4}$	12,4	4,2	292
^{94}Nb	$2.1 \cdot 10^{-5}$				
^{99}Tc	26,7	0,022	13.	694	11.555
^{107}Pd	6.9	0.0033	38.2	527	91
^{129}I	5.6	0.0049	20	224	107
^{135}Cs	43.5	0.0246	42.8	3724	4.288
Sum	82,9	0.055		5173	16.335

C: transmutation is possible , $m_{tr} = 0.5 M$ | $\beta = 5.5\%$.

$$g = 2M \cdot T_{tr}^{1/2} \qquad T_{tr}^{1/2} = 10 \cdot \Phi^{*}/\Phi_{NOM}$$

—— : ——

Fast Reactor BN-1500 $W_T = 3750$ MWt

Low-enrichment zone $\boxed{kg/yr.GW}$ $BR = 1.48$ $3.41 \cdot 10^{20}$ n/s

$\to$ 1.1 BR

0.38 → to Buznez

$V_{core} \sim 4.2 m^3$

Φ^{*}/Φ_{NOM}:	(LiB-1)	(LiB-2)	kg/yr.GW	G, kg.
79Se	0,911	-	49.1	3352
90Sr	29.5	22.	—	—
93Zr	3.3	3.9	57.8	14.365
94Nb	1,2	1.26	58.5	5.300
99Tc	0.54	0.67	61.6	2.480
107Pd	0.351	0.55	66.5	1.755
126Sn	35.8	43.8	—	
129I	0.89	0,81	80	5316
135Cs	1.57	4.4	83.9	9.900
137Cs	13.5	21.9	-	
151Sm	0,17	0,14	93.9	98.6

$$K_i = \frac{m_{tr} - m^{BN}}{m^{RBMK}}$$

BN → can transmutate own FP plus RBMK' FP + Pu.

R: 1) ^{79}Se, ^{99}Tc, ^{107}Pd ^{129}I, ^{151}Sm → $T_{1/2}$ < 10yrs

^{93}Zr ^{94}Nb ^{135}Cs 10 — 50 yrs

for ^{90}Sr, ^{137}Cs $T_{1/2} \le T^{i}_{1/2}$ $\Phi\uparrow$ 4÷8 times

2) without Pu → +50 ÷ 100 kg FP/yr GWt
(own + RBMK' FP)

3) reactor problems

~~4~~ 4 ^{79}Se, ^{99}Tc, ^{107}Pd ^{129}I ^{135}Cs → soft spectrum of graphite (RBMK),

1

BN-1500

Se abs. %	^{76}Se	^{77}Se	^{78}Se	^{79}Se	^{80}Se	^{82}Se
	2-4	9.5	4.9	53.6	23.	9.

Zr abs %	^{91}Zr	^{92}Zr	^{93}Zr	^{94}Zr	^{96}Zr
	0.01	19.8	43.8	13.3	23.1

Pd abs %	^{104}Pd	^{105}Pd	^{106}Pd	^{107}Pd	^{108}Pd	^{110}Pd
	7.9	57.9	8.5	20.8	3.8	1.1

I abs %	^{127}I	^{129}I
	27.1	72.9

abs Cs	133	134	135	137
	80.5	4.8	12.5	2.2

Fusion blanket (OTR/ITER)

$1\,\mathrm{MW/m^2} \rightarrow 4.4 \cdot 10^{13} \dfrac{(14.1\,\mathrm{MeV\ neutrons})}{\mathrm{cm^2 s}}$

$1.2 \div 1.25$ neutrons → tritium breeding

$0.1 \div 0.35$ → 50% structure materials
→ 50% transmutation processes

	^{79}Se	^{99}Tc	^{94}Nb	^{129}I
$\frac{\mathrm{kg}}{\mathrm{GWt\,yr}}$:	165	207	197	270

(n,γ) (n,2n)

Accelerator-driven blanket

	Production (PWR)	Max Transmutation	T/P
^{90}Sr	18 kg/yr	177	9.8
^{93}Zr	24	183	7.8
^{99}Tc	2*	194	7.3
^{107}Pd	6.9	210	30.
^{129}I	5.6	253	46.
^{135}Cs	44	266	6.1
^{137}Cs	40	269	6.7.