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Workshop on

Nuclear Reaction Data and Nuclear Reactors: Physics, Design and Safety

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Miramare - Trieste, Italy

Long Term Radiotoxicity

I. Slessarev
CEA Cadarache
St. Paul Lez Durance, France

WORKSHOP ON NUCLEAR REACTION DATA AND NUCLEAR REACTORS:

Physics, Design, Safety

Trieste, ITALY

Prof. Igor SLESSAREV
CEA, FRANCE

LONG TERM RADIOTOXICITY

April 12 2000

LONG -TERM RADIOACTIVITY AND RADIOTOXICITY OF NUCLEI
as the result
of NUCLEAR ENERGY PRODUCTION

GROUPS of LONG-TERM RADIOACTIVE WASTES:

1.ACTINIDES

2.Long-Lived FISSION PRODUCTs (LLFP)

3.LANTANIDES (LA)
(in connection with discharge fuel reprocessing needs)

Quantitative measure of RADIOTOXICITY

Factor of dose "par ingestion" or "par inhalasion"

$$R(Sv) = F_d\,(Sv/Bq) \times A(Bq)$$

Table. Periods and factor of dose "par ingestion"

Nuclides	Life period (y)	Emission	F_d
Tc-99	$2\ 10^{5}$	β-	$0.64\ 10^{-9}$
I-129	$1.6\ 10^{7}$	β-	$0.11\ 10^{-6}$
Pu-238	88	α	$0.23\ 10^{-6}$
Pu-239	$2.4\ 10^{4}$	α	$0.25\ 10^{-6}$
Am-241	432	α	$0.20\ 10^{-6}$
Am-243	$7.4\ 10^{3}$	α	$0.20\ 10^{-6}$
Cm-244	18	α	$0.16\ 10^{-6}$

TOXICITY

TABLEAU

On donne les logarithmes décimaux des facteurs de danger ingestif (en Sv/g initial du noyau considéré) à diverses échéances. Les familles de décroissance pour les actinides sont les suivantes:

1	décroît sur	Pb206
2	"	Pb207
3	"	Pb208
4	"	Bi209

Th232 -2,28 -2,28 -2,28 -2,29 -2,28 -2,28 -2,28

Noyau	Famille	10^2 ans	10^3 ans	10^4 ans	10^5 ans	10^6 ans	10^7 ans	10^8 ans
U232	3	5.22	1.35	-3.74	-	-	-	-
U233	4	1.47	1.78	2.40	2.43	0.72	-16.43	-
U234	1	1.22	1.24	1.65	2.35	1.57	-9.49	-
U235	2	-2.19	-1.78	-0.96	-0.31	-0.26	-0.26	-0.30
U236	3	-0.79	-0.79	-0.79	-0.80	-0.81	-0.92	-1.88
U238	1	-3.08	-3.08	-3.06	-2.53	-1.66	-1.62	-1.62
Np237	4	1.44	1.44	1.45	1.56	1.63	0.37	-12.29
Pu236	3	5.23	1.36	-3.73	-	-	-	-
Pu238	1	5.46	2.41	1.64	2.34	1.56	-9.49	-
Pu239	2	3.43	3.41	3.30	2.17	-0.27	-0.27	-0.31
Pu240	3	3.99	3.94	3.53	-0.40	-0.81	-0.93	-1.89
Pu241	4	5.13	4.50	1.44	1.55	1.62	0.36	-12.30
Pu242	1	2.20	2.20	2.20	2.12	1.40	-1.63	-1.63
Pu244	3	-0.14	-0.10	0.08	0.17	0.16	0.13	-0.18
Am241	4	5.11	4.49	1.44	1.55	1.62	0.36	-12.30
Am242m	1	5.61	3.97	1.79	2.30	1.53	-2.39	-2.39
Am243	2	3.94	3.92	3.68	2.33	-0.27	-0.28	-0.32
Cm242	1	5.45	2.40	1.63	2.33	1.55	-9.50	-
Cm243	2	5.13	3.41	3.30	2.17	-0.27	-0.28	-0.32
Cm244	3	4.68	3.94	3.52	-0.40	-0.82	-0.93	-1.90
Cm245	4	3.93	4.11	3.85	1.59	1.62	0.35	-12.31
Cm246	1	4.13	4.07	3.51	2.12	1.40	-1.63	-1.64
Cm247	2	0.59	0.62	0.82	1.06	1.06	0.89	-0.21
Cm248	3	2.84	2.84	2.83	2.75	1.96	0.13	-0.19

Pa-231 4,06 4,06 3.98 3.16 -5.1 -27.7 —

Noyau	10^2 ans	10^3 ans	10^4 ans	10^5 ans	10^6 ans	10^7 ans	10^8 ans
Se79	0.77	0.77	0.73	0.31	-3.85	-	-
Zr93	-1.41	-1.41	-1.41	-1.43	-1.60	-3.38	-
Nb94	0.99	0.97	0.84	-0.50	-13.84	-	-
Tc99	-0.67	-0.67	-0.69	-0.81	-2.08	-14.80	-
Pd107	-3.15	-3.15	-3.15	-3.16	-3.20	-3.62	-7.78
Sn126	0.76	0.76	0.73	0.46	-2.25	-	-
I129	-0.32	-0.32	-0.32	-0.32	-0.33	-0.51	-2.23
Cs135	-1.09	-1.09	-1.09	-1.10	-1.22	-2.40	-14.18

TABLEAU

On donne les logarithmes décimaux des activités (en Bq/kg initial du noyau considéré) à diverses échéances. Les familles de décroissance pour les actinides sont les suivantes:

1 décroît sur Pb206
2 " Pb207
3 " Pb208
4 " Bi209

Noyau	Famille	10^2 ans	10^3 ans	10^4 ans	10^5 ans	10^6 ans	10^7 ans	10^8 ans
U232	3	15.39	11.52	-2.72	-	-	-	-
U233	4	11.59	11.79	12.31	12.34	10.62	-6.52	-
U234	1	11.36	11.37	11.58	12.12	11.33	0.27	-
U235	2	8.21	8.24	8.47	8.90	8.95	8.94	8.90
U236	3	9.38	9.38	9.38	9.38	9.37	9.25	8.20
U238	1	7.57	7.57	7.57	7.70	8.21	8.24	8.23
Np237	4	10.71	10.72	10.75	11.10	11.34	10.08	-2.58
Pu236	3	15.40	11.53	-2.72	-	-	-	-
Pu238	1	14.46	11.67	11.57	12.12	11.32	0.26	-
Pu239	2	12.36	12.35	12.24	11.11	8.94	8.94	8.90
Pu240	3	12.92	12.88	12.47	9.41	9.36	9.25	8.20
Pu241	4	14.16	13.42	10.74	11.09	11.33	10.07	-2.59
Pu242	1	11.16	11.16	11.15	11.08	10.36	8.23	8.22
Pu244	3	9.30	9.31	9.38	9.42	9.42	9.41	9.18
Am241	4	14.03	13.41	10.74	11.09	11.33	10.07	-2.59
Am242m	1	14.75	13.05	11.51	12.03	12.41	7.47	7.46
Am243	2	13.17	13.13	12.84	11.26	8.93	8.93	8.89
Cm242	1	14.45	11.67	11.56	12.11	11.31	0.26	-
Cm243	2	14.23	12.34	12.23	11.10	8.93	8.93	8.89
Cm244	3	13.85	12.87	12.46	9.40	9.35	9.24	8.19
Cm245	4	13.12	13.22	12.94	11.08	11.33	10.07	-2.59
Cm246	1	13.05	12.99	12.44	11.08	10.36	8.22	8.22
Cm247	2	9.84	9.87	10.06	10.23	10.22	10.05	8.99
Cm248	3	11.20	11.20	11.19	11.11	10.35	9.40	9.17

PHYSICS of TRANSMUTATION: POTENTIAL, principal CONSTRAINTS

Neutronics plays a most important role in transmutation potential

Fig. "Transmutation sieve"

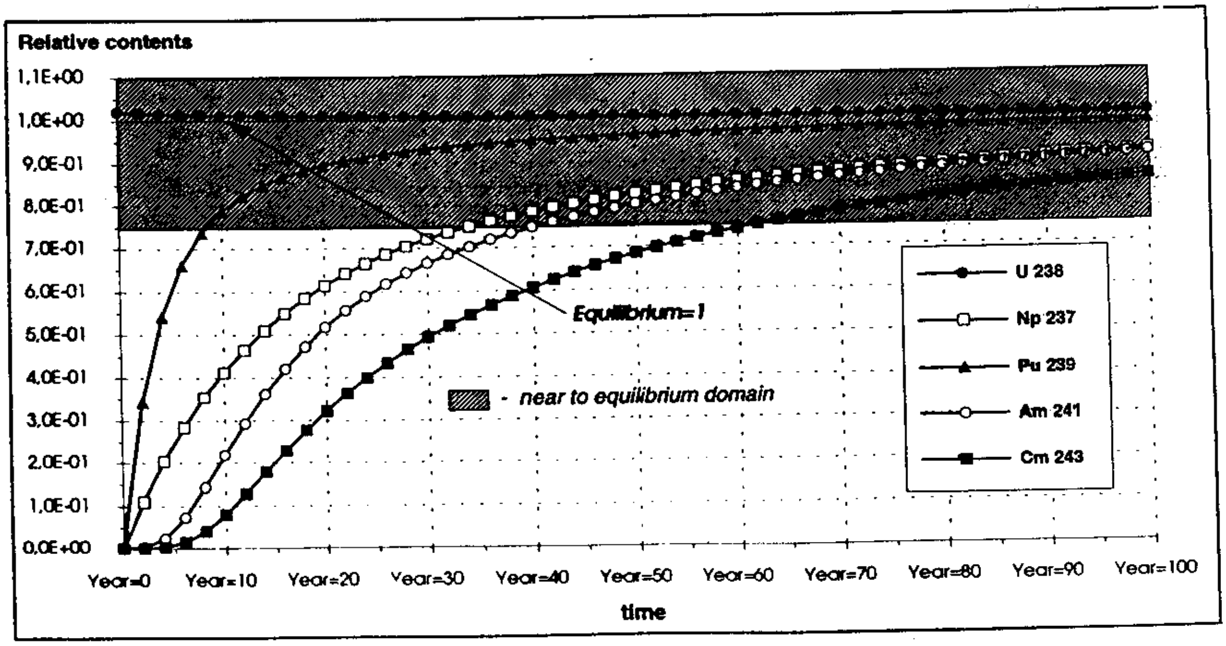
Overall neutron balance for nuclide family library (at equilibrium)

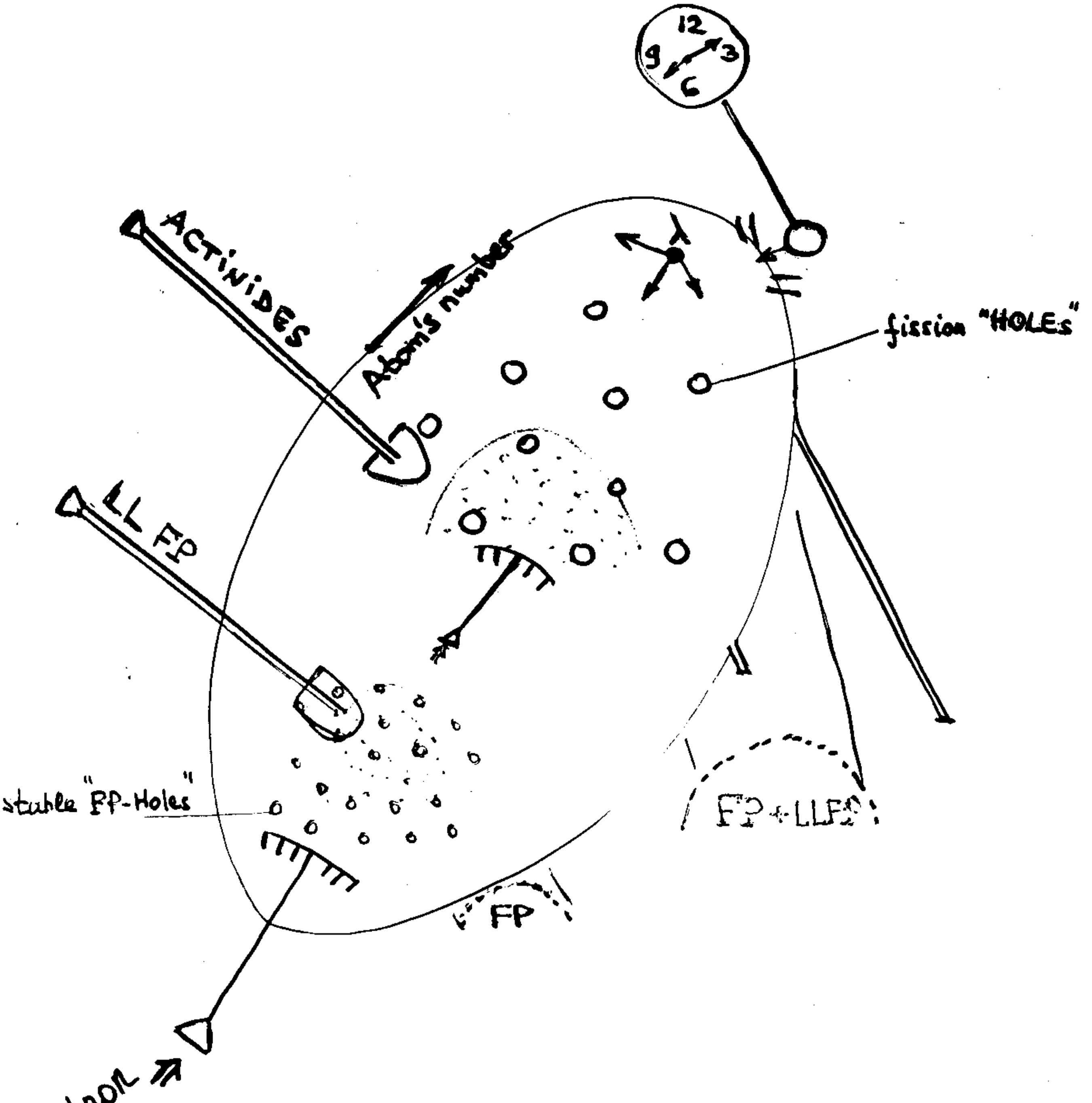
Equilibrium:

"Family" is a set of nuclei (including the initial nucleus) which have been produced both by transmutation in a neutron flux Φ of the nucleus as well as of its subsequent products, and by decay of nuclei.

The equilibrium state of a family in a given nuclear system is the relative concentration distribution N of this family members for the asymptotic (t→∞) condition when a given system is continuously fed by the initial nucleus only

The analysis of a transient time shows that in the case of the main families (such as ^{238}U, ^{235}U) the rate of convergence to equilibrium even for standard neutron fluxes level is high enough.





TRANSMUTATION
"SIEVE"

Equilibrium concentrations have been obtained as solution of the following equations (BATEMAN):

$$\boxed{dN_J/dt = (M\Phi - \Lambda - L)\cdot N_J - S_J = 0}$$

where :

M -- the operator of a nucleus transmutation by means of the corresponding neutronic processes (capture, fission, (n,2n), (n,3n) reactions, etc.),

Φ -- a neutron flux,

Λ -- the operator of decay : α, β^+, β^-, etc.,

L -- the operator of nuclei "*losses*"
(more generally, the operator of nuclei extraction rate) from fuel cycle
(e.g. losses during reprocessing),

S_J -- a source of the J-family (reactor feed rate).

Family Overall Neutron Consumption

Decay, irradiation and regular discharge (or losses) of every nucleus J (family "father") in a neutron flux produce at equilibrium (see equation (1)) the J-nucleus family.

Then one can calculate the total number of neutrons D_J which have been consumed by this family to be burnout transmuted to either stable or short lived nucleus and then extracted from this system).

If a given system is fed by a set of J-nuclei then the potential neutron surplus **G** will be defined by a sum of all D_J (neutron consumption), the neutron losses of this system and supplementary neutrons (μ) (in ADS) :

$$G\,(neutrons\,/\,fission) = -\sum_J X_J \cdot D_J - 0.3 + \mu = \sum_J X_J \cdot G_J + \mu = G_0 + \mu\ .$$

where X_J is a fraction of J-nucleus in fuel feed.

SPECIFIC FEATURES OF TRANSMUTATION. NEUTRONICS

Actinide Toxicity after Fuel Irradiation

Individual nuclear family toxicities depends on

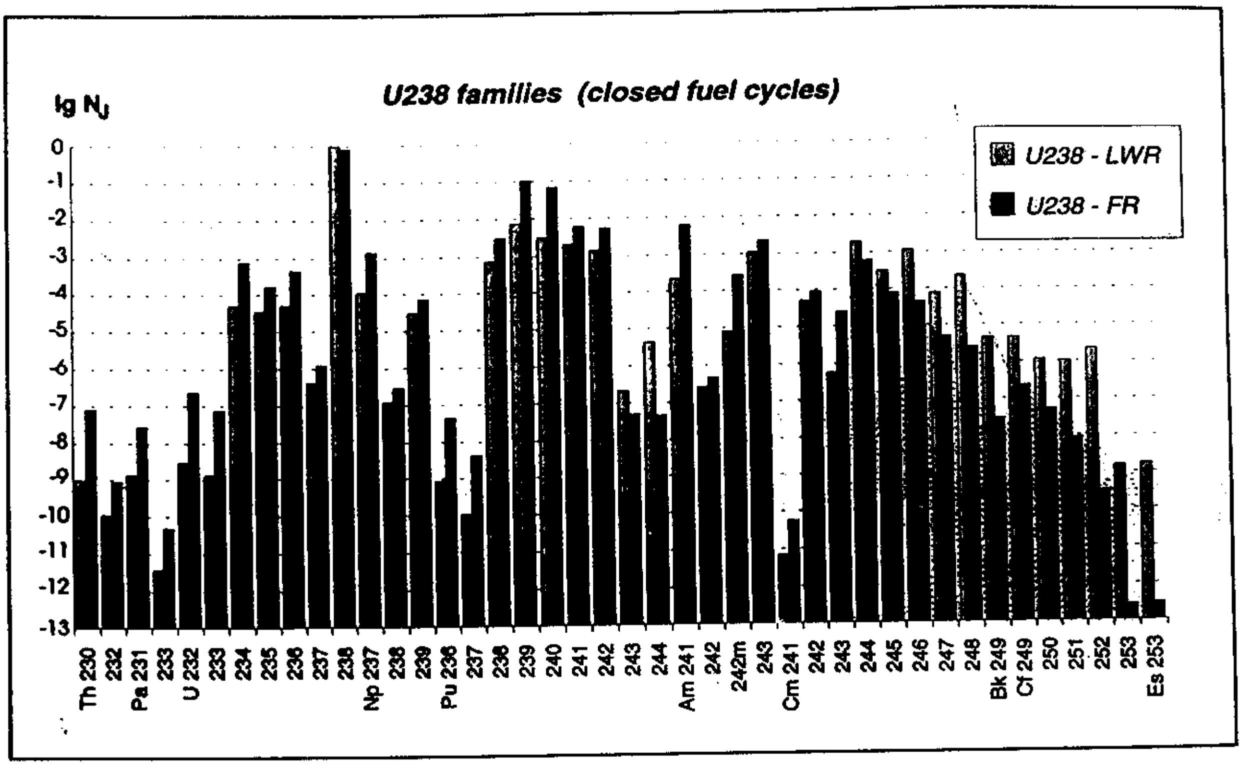
- *initial nuclide ("father")*
- *neutron flux level,*
- *neutron spectrum*
- *fuel cycle parameters*
  (burnup via discharge period, losses, etc.)

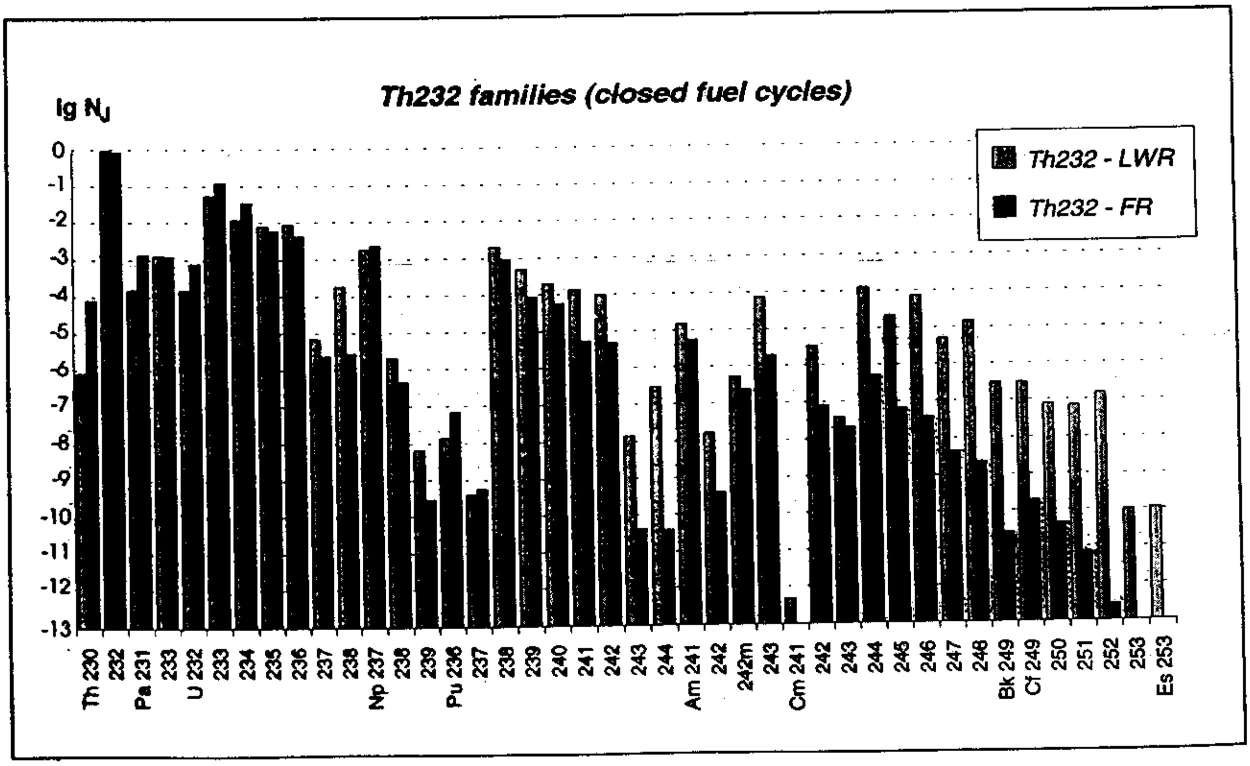
TABLE II

Normalised toxicities of J-families τ_J at equilibrium (Sv/gram); τ_J have been averaged on Short ($10^2 \div 10^4$ years) and Long ($10^2 \div 10^6$ years) time intervals (negligible losses rates)

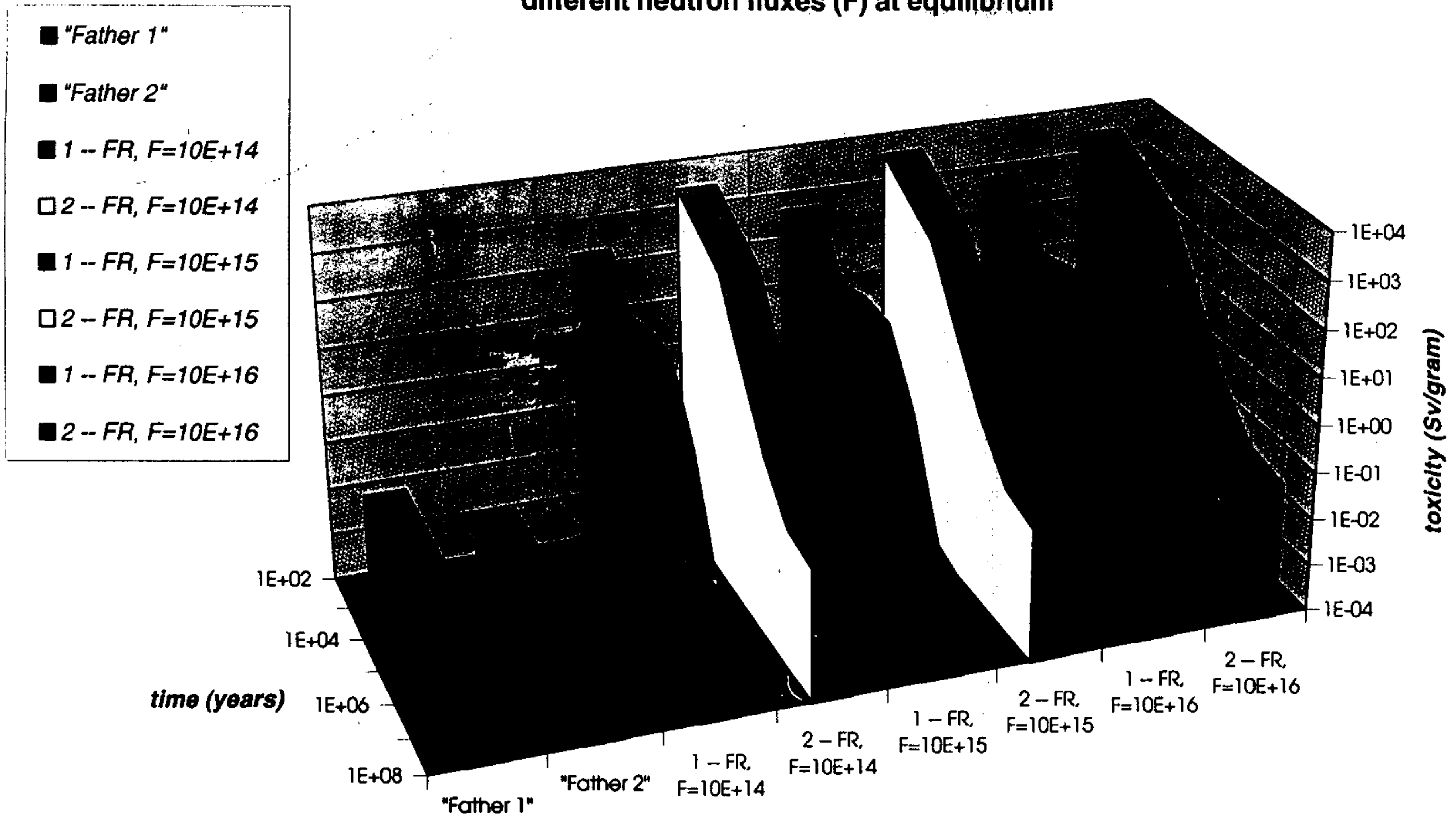
	Thermal Reactors ($\Phi = 10^{14}$ n/cm^{2}s)		Fast Reactors ($\Phi = 10^{15}$ n/cm^{2}s)		Super-thermal Reactors ($\Phi = 10^{16}$ n/cm^{2}s)		Natural Toxicity ($\Phi = 0$ n/cm^{2}s)	
"*fathers*" of families	τ_J Short	τ_J Long	τ_J Short	τ_J Long	τ_J Short	τ_J Long	τ_J Short	τ_J Long
^{232}Th	21	4.6	38	11	41	3.8	0.0052	0.0052
^{231}Pa	5364	47	7583	31	3633	36	10570	0.3
^{233}U	221	53	117	62	168	23	111	46
^{235}U	372	19	92	19	173	2.5	0.037	0.48
^{238}U	97	1	841	5.7	275	3.5	0.0008	0.0068
^{237}Np	1436	71	318	65	1984	55	28	39
^{238}Pu	2120	77	751	86	4411	63	164	90
^{239}Pu	4851	46	4290	28	4610	58	2300	13
^{240}Pu	5952	50	6025	22	4723	59	5730	0.41
^{241}Pu	5834	62	4506	63	4661	62	1430	38
^{242}Pu	5139	58	3106	56	5883	60	160	63
^{241}Am	3869	72	3826	67	6019	63	1410	38
^{242m}Am	6222	60	5128	74	6125	62	1180	85
^{243}Am	6277	55	6557	32	6120	61	6500	17
^{242}Cm	2051	78	798	86	2626	86	161	88
^{244}Cm	6135	53	6264	19	6058	61	6140	0.4
^{245}Cm	5942	101	7939	71	5876	97	9640	52

Equilibrium concentration distributions

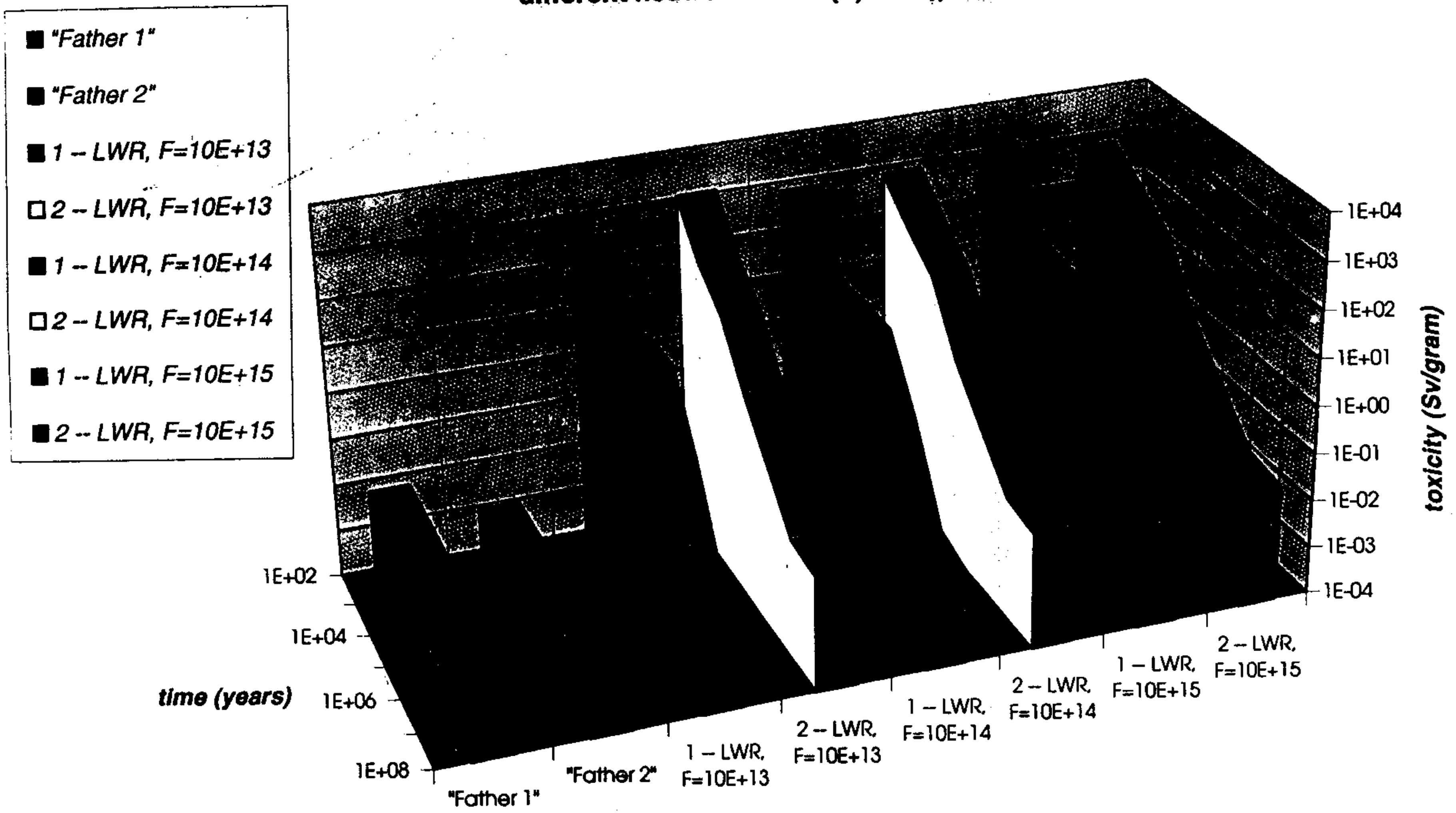




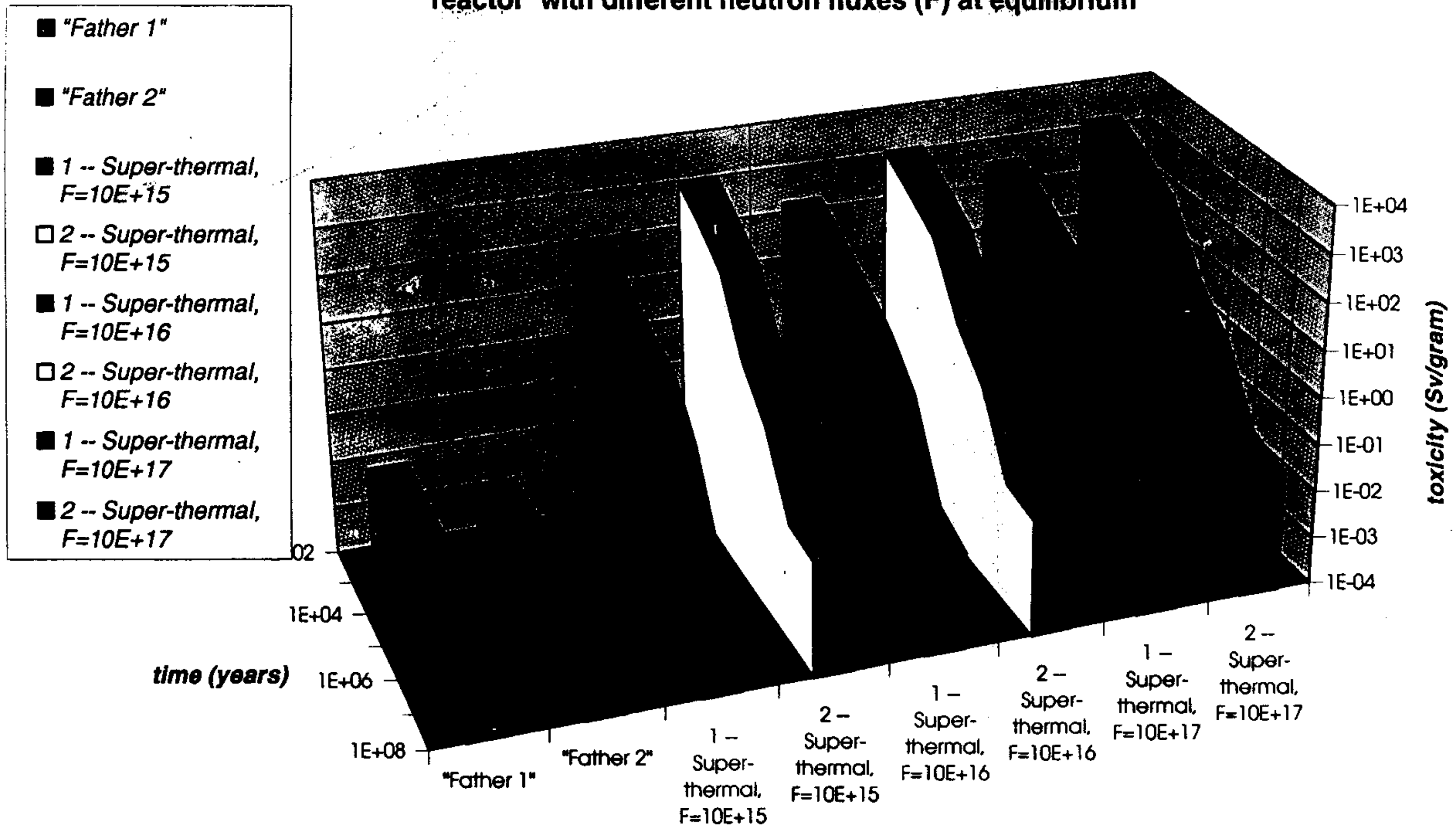
Toxicity of Th232 ("father 1"), U238 ("father 2") and their "families" in FR with different neutron fluxes (F) at equilibrium



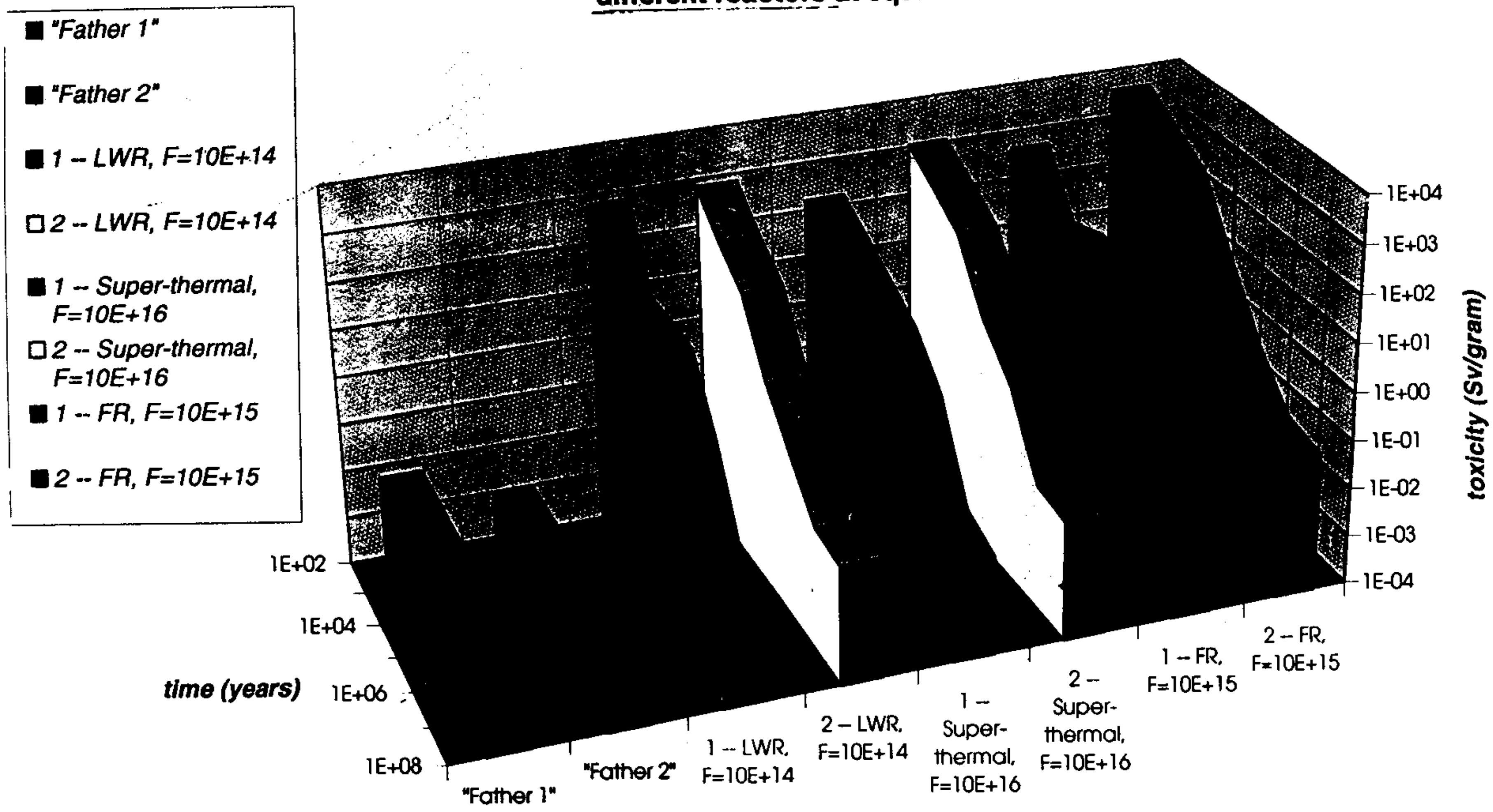
Toxicity of Th232 ("father 1"), U238 ("father 2") and their "families" in LWR with different neutron fluxes (F) at equilibrium



Toxicity of Th232 ("father 1"), U238 ("father 2") and their "families" in Super-thermal reactor with different neutron fluxes (F) at equilibrium

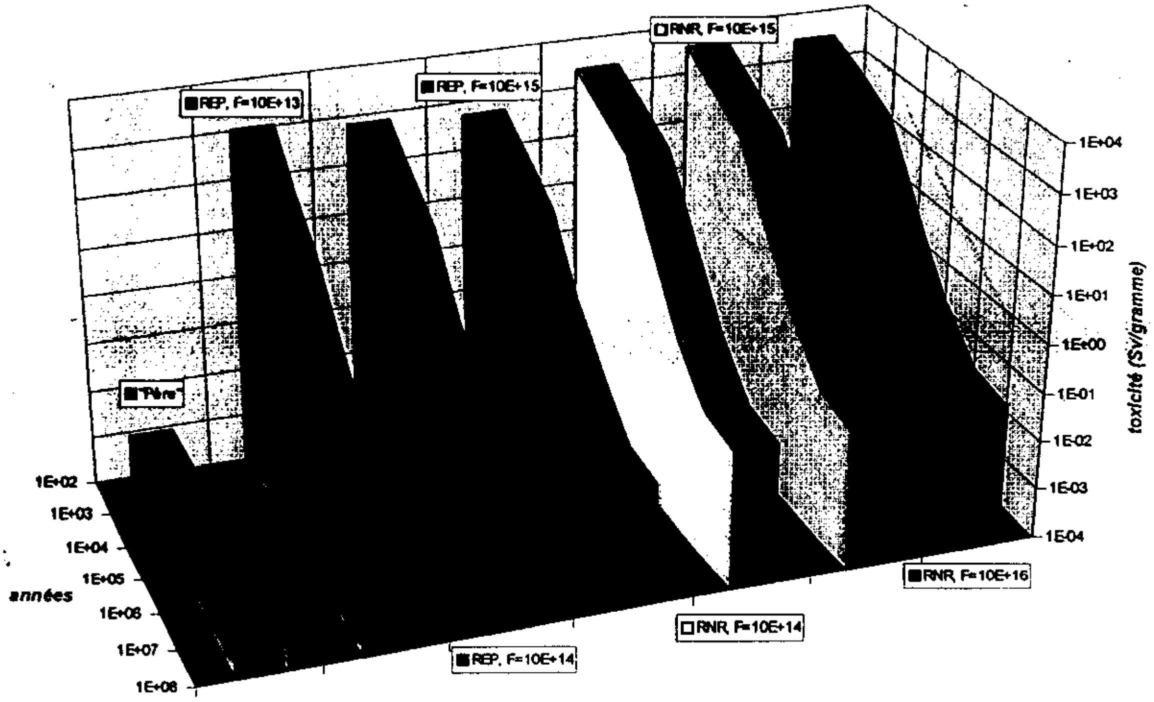


Toxicity of Th232 ("father 1"), U238 ("father 2") and their "families" in different reactors at equilibrium

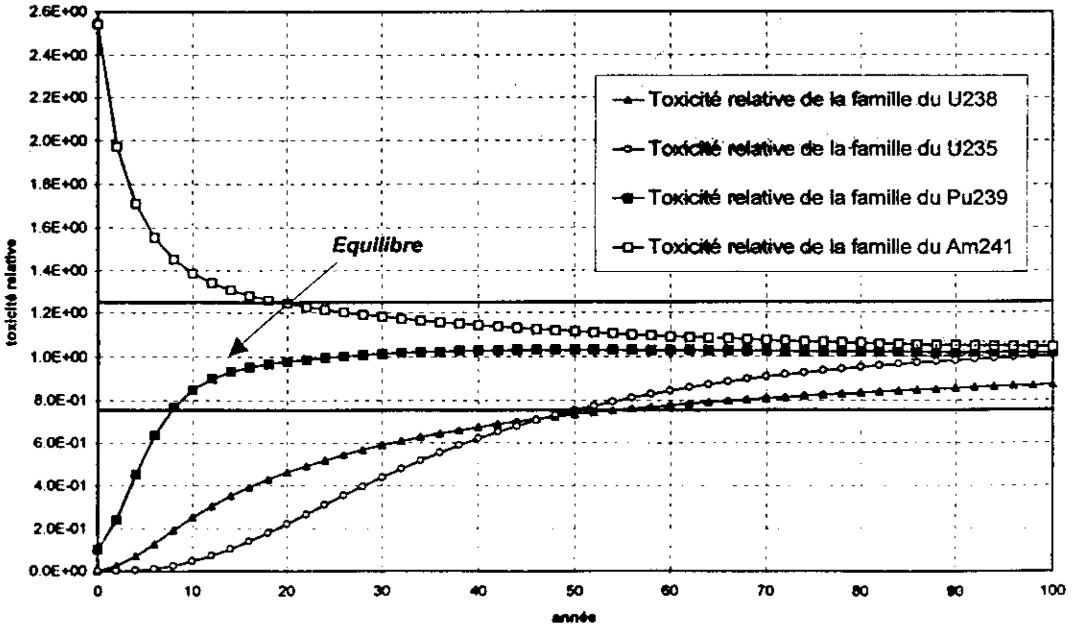


Toxicités à l'équilibre

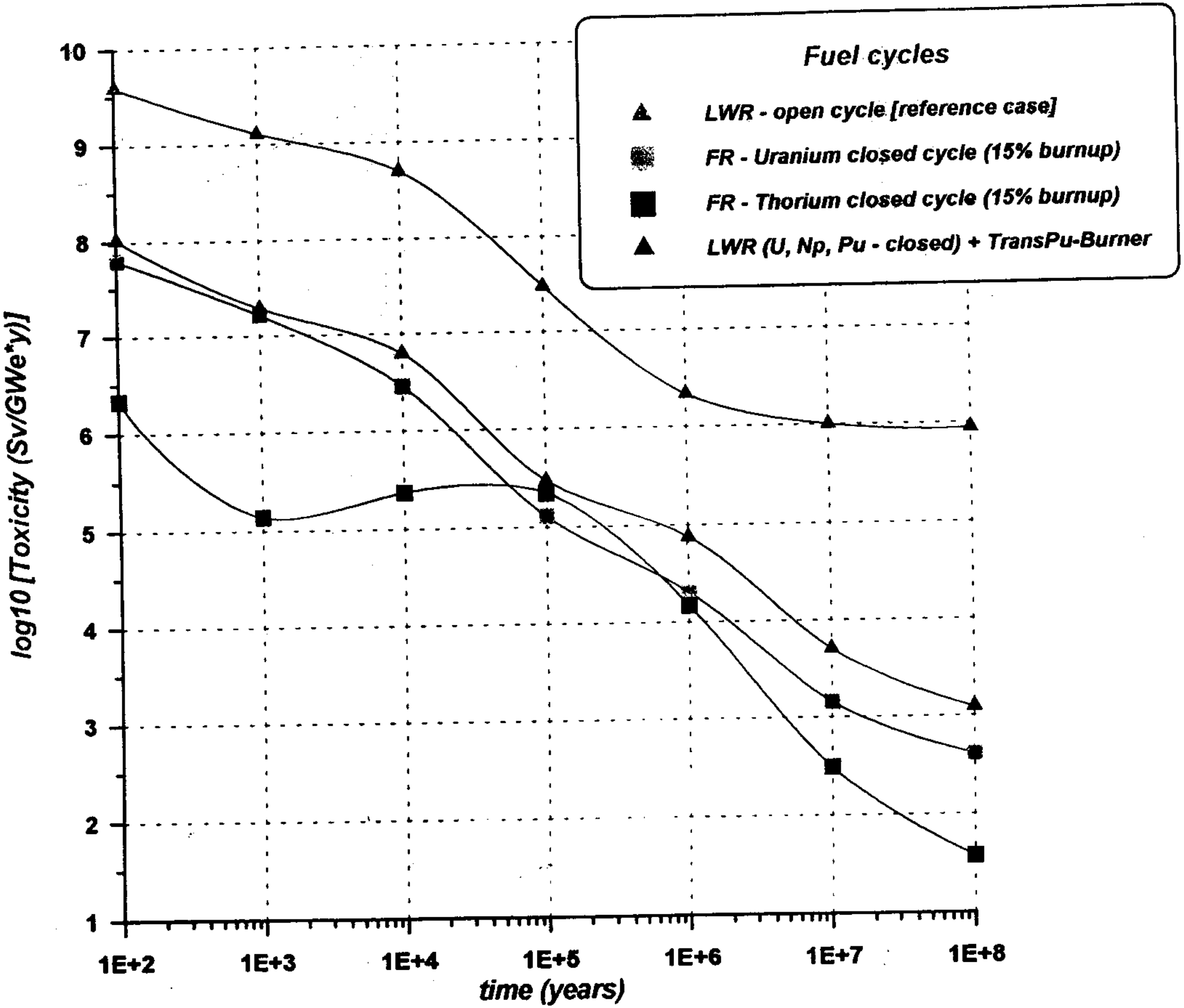
Toxicité du U238 ("père") et de sa "famille" dans les différents réacteurs et les flux neutroniques (F) en équilibre



Convergence relative de la toxicité (après 100 ans de refroidissement) pour les familles principales en REP standard



Fuel Waste Toxicity reduction potential



LLFP TRANSMUTATION
is IMPORTANT
because of
- non-negligible toxicity,
- essential MOBILITY

Time T_J^{transm} needed to incinerate half of initial mass which is a function of the cross-section $\sigma^J_{n,\gamma}$ (barns) and of the neutron flux Φ (n/cm^{2}s) is:

$$T_J^{transm} = \frac{\ln 2}{\sigma^J_{n,\gamma}\,\Phi \times 3.16 \times 10^7}\, years$$

Transmutation under neutron flux can be reasonable
if $T1/2 >> T_J^{transm}$ and
if this time is technologically acceptable

TABLE I

Parameters of long lived nuclei to be eventually transmuted in a fast
(E_n (neutron energy) = 0.2 MeV, JEF-2.2) and "thermal" (E_n = 1 eV, JEF-2.2)
spectra with standard flux levels : $\Phi = 10^{15}$ (n/cm^{2}s) $\Phi = 10^{14}$ (n/cm^{2}s) correspondingly

Isotopes, *J*	$\sigma^J_{n,\gamma}$ (barns)		*T*1/2 (years)	T_J^{transm} (years)		**Radio-toxicity in** (Sv/g) at $t = T_J^{transm}$	**Recommendation** to transmutation
	fast spectrum	**thermal** spectrum		**fast** spectrum	**thermal** spectrum		
^{79}Se	0.03	0.1	6.5×10^4	7.3×10^2	2.2×10^3	6.0	*questionable*
^{90}Sr	0.01	0.14	29	2.2×10^3	1.6×10^3	-	*non-transmutable*
^{93}Zr	0.03	0.28	1.5×10^6	730	790	0.04	*questionable*
^{94}Nb	0.04	2.2	2.0×10^4	5.5×10^2	1×10^2	9.0	*questionable or transmutable*
^{99}Tc	0.2	4.3	2.1×10^5	110	51	0.2	***transmutable***
^{107}Pd	0.5	0.3	6.5×10^6	44	730	0.0007	***transmutable***
^{126}Sn	0.005	0.05	1×10^5	4.4×10^3	4.4×10^3	4.0	*questionable*
^{129}I	0.14	4.3	1.6×10^7	160	51	0.5	***transmutable***
^{135}Cs	0.07	1.3	2.3×10^6	310	170	0.08	***transmutable***
^{137}Cs	0.01	0.02	30	2.2×10^3	1.1×10^4	-	*non-transmutable*
^{151}Sm	0.7	700	89	31	0.3	-	*non-transmutable or questionable*

AXIOMS

A1. For a given neutron spectrum:

THE MAXIMUM SPECIFIC (per power unit) RATE OF LLFP-TRANSMUTATION
(the number of transmutations per fission)
IS EQUAL TO THE NEUTRON SURPLUS PRODUCED BY (FUEL + S).

A2.

THE REAL LLFP-TRANSMUTATION RATE IS DEFINED BY THE DISTRIBUTION OF THE NEUTRON SURPLUS BETWEEN COMPETITORS: such as LLFP, CONSTRUCTION MATERIALS, NEUTRON LEAKAGE, etc

If required transmutation rates are comparable in the value with real neutron surpluses of fuels

(industrial transmutation scale!)

there is the single principal way to increase the LLFP transmutation rate:

the proper choice of both neutron spectrum and fuel:

TWO LLFP TRANSMUTATION PROBLEMS

- TRANSMUTATION RATE MAXIMISATION
  (number of LLFP-transmutations per fission)
  via
  NEUTRON PRODUCTION POTENTIAL ENHANCEMENT

- LLFP INVENTORY MINIMISATION

OVERALL NEUTRON CONSUMPTION OF LLFP NEEDED FOR THEIR TRANSMUTATION

DEFINITION : J-family is a set of nuclei (including the initial nucleus J) which have been produced both by the transmutation in a neutron flux Φ of the J nucleus as well as of its subsequent products, and by decay of nuclei.

The overall neutron consumption D_J of the LLFP family (*J*-family) can be defined as the total number of neutrons which have to be spent to incinerate the whole family. Removal of stable and short lived fission products can be considered as a single sink of long-term radioactive fission products.

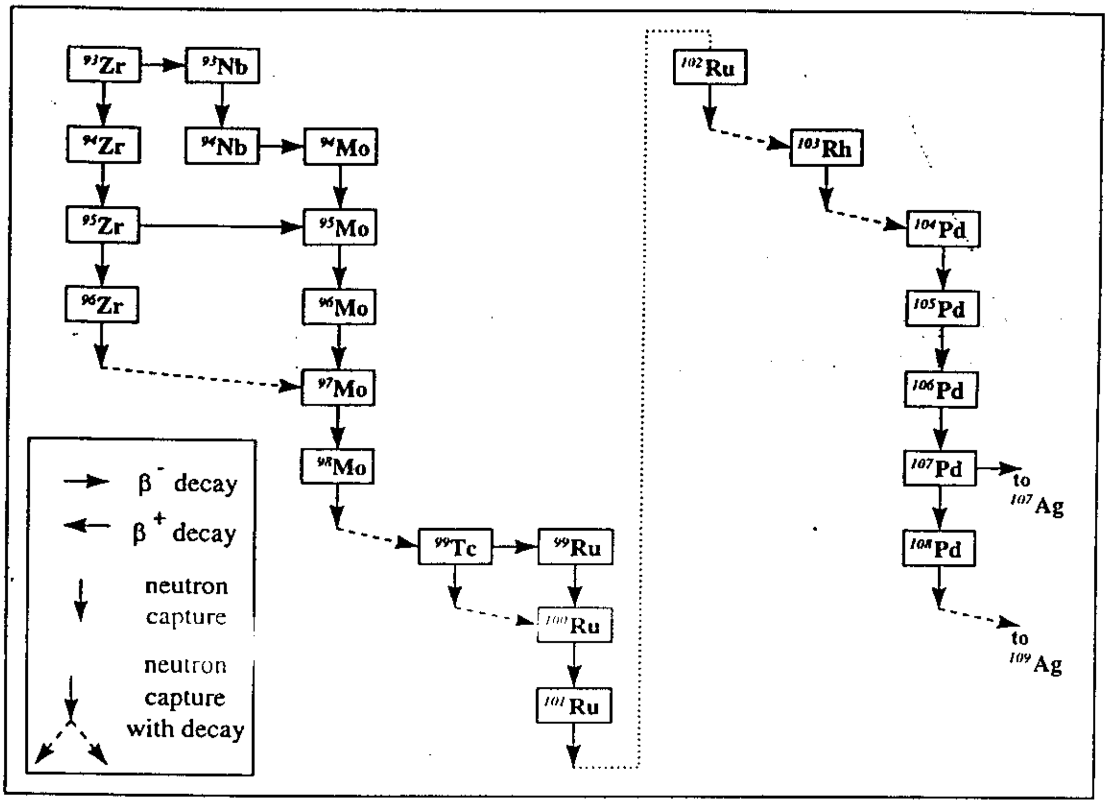


Fig. 1. LLFP transmutation scheme.

TABLE 2

Overall neutron consumption (D_J^*) of "*transmutable*" and "*questionable*" isotopes together with their yields (Y_J) per *1* fission in LWR (UOX) after 5 years of cooling time. Time interval between reprocessing steps - 3 years (removable nuclides : all fission products except all isotopes of *Zr, Tc, Pd, I, Cs, Sn, Nb, Se*)

Transmutable and questionable isotopes (J)	D_J^* neutron/transmutation	Y_J nuclei/fission in NP
^{93}Zr	2.01	0.050
^{99}Tc	1.01	0.055
^{107}Pd	2.04	0.015
^{129}I	1.008	0.009
^{135}Cs	1.002	0.017
^{126}Sn	~2	0.0012
^{94}Nb	0.985	6.3×10^{-7}
^{79}Se	~2	0.0004

TABLE 3

Overall neutron consumption (D^*_J) of "*transmutable*" nuclides (including all isotopes) together with their yields (Y_J) per *1* fission in LWR (UOX) after 5 years of cooling time. Time interval between fission products reprocessing - 3 years (removable nuclides : all fission products excluding all isotopes of *Zr, Tc, Pd, I, Cs*)

Transmutable nuclides, *J*	D^*_J (neutron/transmutation)	Y_J (nuclei/fission in NP)
all *Zr*	2.03	0.26
all *Tc*	1.01	0.055
all *Pd*	3.22	0.095
all *I*	1.01	0.011
all *Cs*	0.585	0.13

TABLE 4

Comparison of overall neutron consumption *D* (neutron/fission in NP)

and

LLFP transmutation effect (reduction of radio-toxicity) for groups of nuclei

$D = D^* \times Y$

Transmutable nuclides	***D*** **(neutron/fission in NP)**	**Radio-toxicity reduction factor for *t* = 1000 years ($Sv/GW_e \times year$)**
^{99}Tc	**0.055**	5500
$^{129}I + ^{99}Tc$	**0.064**	8160
$^{129}I + ^{99}Tc + ^{135}Cs$	**0.081**	9060
all isotopes of *Tc, I, Cs*	**0.15**	9060
all isotopes of *Tc, I, Cs + Zr*	**0.68** <too many!>	9930
all isotopes of *Tc, I, Cs +Zr + Pd*	**0.98**<too many!>	9935

TABLE 5

RADIOTOXICITY of U being eliminated by NP (LWR's)

years	10^2	10^3	10^4	10^5	10^6	10^7	10^8
radio-toxicity	5×10^4	6×10^4	2×10^5	1×10^6	4×10^5	4×10^5	4×10^5

TABLE 6

Radio-toxicity of long-lived LLFP in the repository

after elimination of Tc, I, Cs ($Sv/GW_e\times year$)

years	10^2	10^3	10^4	10^5	10^6	10^7	10^8
radio-toxicity	4.9×10^3	4.9×10^3	4.6×10^3	2.3×10^3	$\sim0.5\times10^3$	~0	~0

AS THE RESULT:

$$TOX_{LLFP} < (TOX_U)/10$$

(THERE IS A MARGIN TO COMPENSATE A MOBILITY OF THE REST LLFP's!)

IT CORRESPONDS TO THE GENERAL "CLEAN ENERGY PRINCIPLE":

TOTAL WASTE TOXICITY PRODUCED BY NUCLEAR POWER HAS NOT TO EXCEED THE TOTAL TOXICITY ELIMINATED BY NUCLEAR POWER

Neutron SURPLUS PRODUCTION Potential (FUEL + EXTERNAL SOURCE)

$$\boxed{G = -\sum_{J} f_J \times D_J - (CM + L) + S}$$

$$G_{TRU} = 1.11 - 0.3 + 0.15 \,\Big|_{\mathrm{Keff} = 0.95} = 0.96 \text{ neutron/fission}$$

$$G_{TRPu} = 0.72 - 0.3 + 0.15 = 0.57 \text{ neutron/fission}$$

REMARK - PARK of LLFP-Burners

If the fast spectrum TRU transmuter ($G = 0.96$ neutron/fission) is used both for the TRU transmutation and *Tc*, *I*, *Cs* incineration, then the fraction ε :

$$\varepsilon \geq \frac{0.15\ neutron\ /\ fission}{G = 0.96\ neutron\ /\ fission} \approx 0.16$$

CONCLUSION

The industrial scale of the LLFP incineration requires an essential number of neutrons.

Hence, fast neutron spectrum and external neutron source (e.g. ADS) are favourable for this application.

RECOMMENDATIONS towards RADIOLOGICAL CLEAN NP

- to put "*transmutable*" (*Tc*, *I* and *Cs*) fission products in fast reactors and/or ADS,
- to put "*non-transmutable*" nuclides such as *Sr*, *Sm* to an interim storage for decaying (during some hundreds years) and eventually directly - to a geological repository,
- to put all "*questionable*" nuclides (*Se*, *Nb*, *Sn*) together with "*transmutable*" *Zr* and *Pd* to a geological repository (an interim storage can be used for the first hundreds years, similar to "*non-transmutable*" nuclides),
- to put all short lived nuclides into an interim storage and then to a geological repository.

To optimise LLFP transmutation, one needs

- ***To use a spectrum with a highest neutron production surplus potential ⇒***

  HIGHEST LLFP TRANSMUTATION RATE

  (FAST neutron spectrum)

- ***To minimise LLFP INVENTORY***

by

**neutron leakage minimisation,*

**minimisation of "parasitic" neutron consumption...),*

via

neutron spectrum thermalisation including LLFP location area,

LLFP resonance capture effects application (TARC),

....

CONSUMPTION OF NEUTRONS BY LANTHANIDES

(D^* of the LANTHANIDES)

REASON: problems of separation LA and TRU

1. YIELDs

Example: fission's in fast spectrum

TOTAL YIELD: ~ 25 % of FP

Isotopes compositions:

La	0.146
Ce	0.309
Pr	0.166
Nd	0.231
Pm	0.0440
Sm	0.0740
Eu	0.0230
Gd	0.00686
Tb	0.000283
Dy	0.000174
Ho	0.0000066
Er	0.0000032
Tm	0.00000015
Yb	0.000000029
Lu	0.0000000007

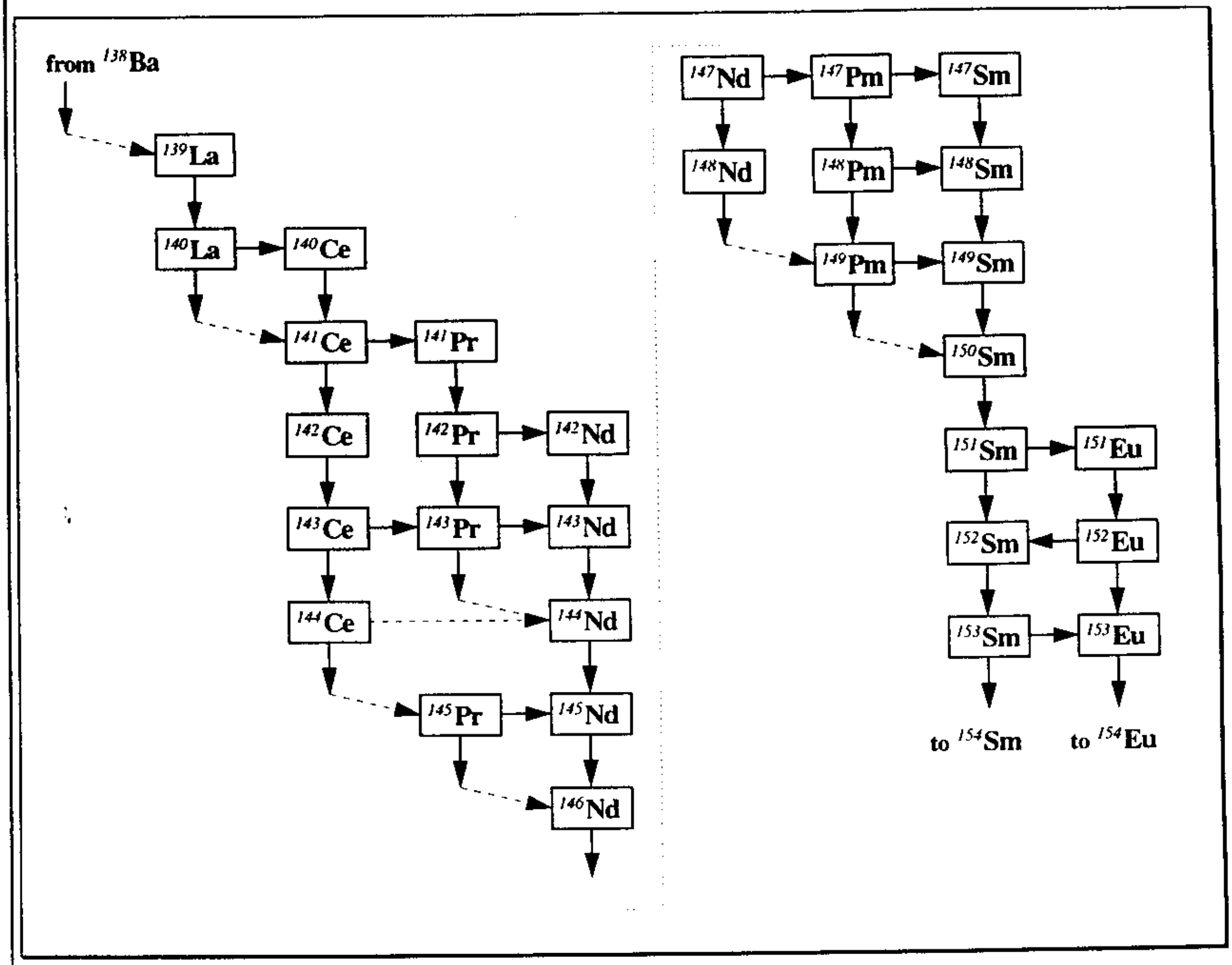
continuation

Table. D* (neutrons per incineration) for Lantanides

Spectrum/Flux	10^{13}	10^{14-}	10^{15}	10^{16}
FAST	**33.5**			
THERMAL	**33.9**			

Table. D* (neutrons per incineration) for Lantanides family (Fast spectrum, Flux: 10^{15} n cm^{-2}s^{-1})

Isotope	D*
La	0.52
Ce	0.47
Pr	0.42
Nd	2.36
Pm	0.23
Sm	3.71
Eu	1.87
Gd	2.98
Tb	1.21
Dy	3.26
Ho	0.71
Er	2.55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¹⁴⁰La
¹⁴⁰Ce
¹⁴¹Ce
¹⁴¹Pr
¹⁴²Ce
¹⁴²Pr
¹⁴²Nd
¹⁴³Ce
¹⁴³Pr
¹⁴³Nd
¹⁴⁴Ce
¹⁴⁴Nd
¹⁴⁵Pr
¹⁴⁵Nd
¹⁴⁶Nd
¹⁴⁷Nd
¹⁴⁷Pm
¹⁴⁷Sm
¹⁴⁸Nd
¹⁴⁸Pm
¹⁴⁸Sm
¹⁴⁹Pm
¹⁴⁹Sm
¹⁵⁰Sm
¹⁵¹Sm
¹⁵¹Eu
¹⁵²Sm
¹⁵²Eu
¹⁵³Sm
¹⁵³Eu
to ¹⁵⁴Sm
to ¹⁵⁴Eu

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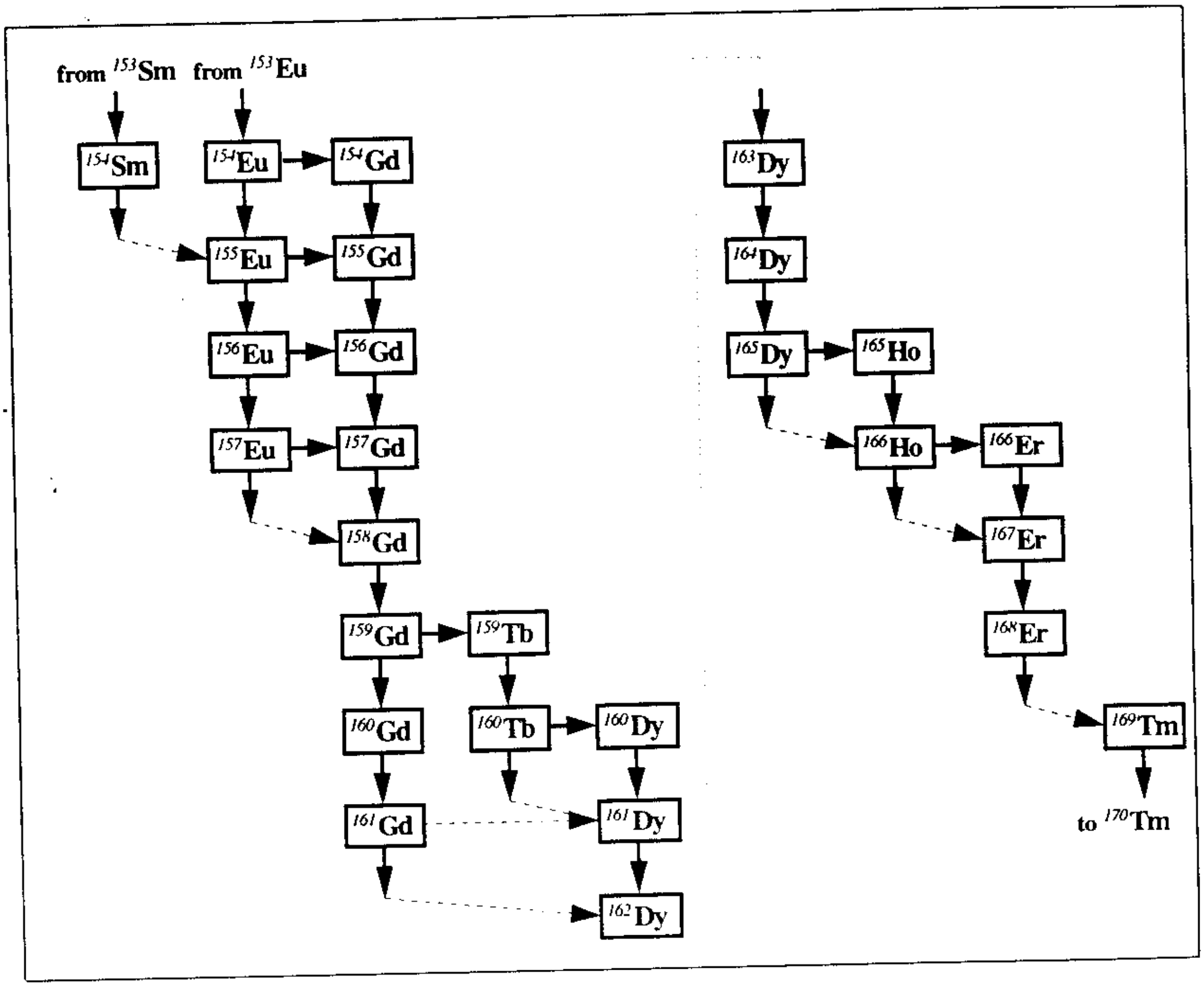
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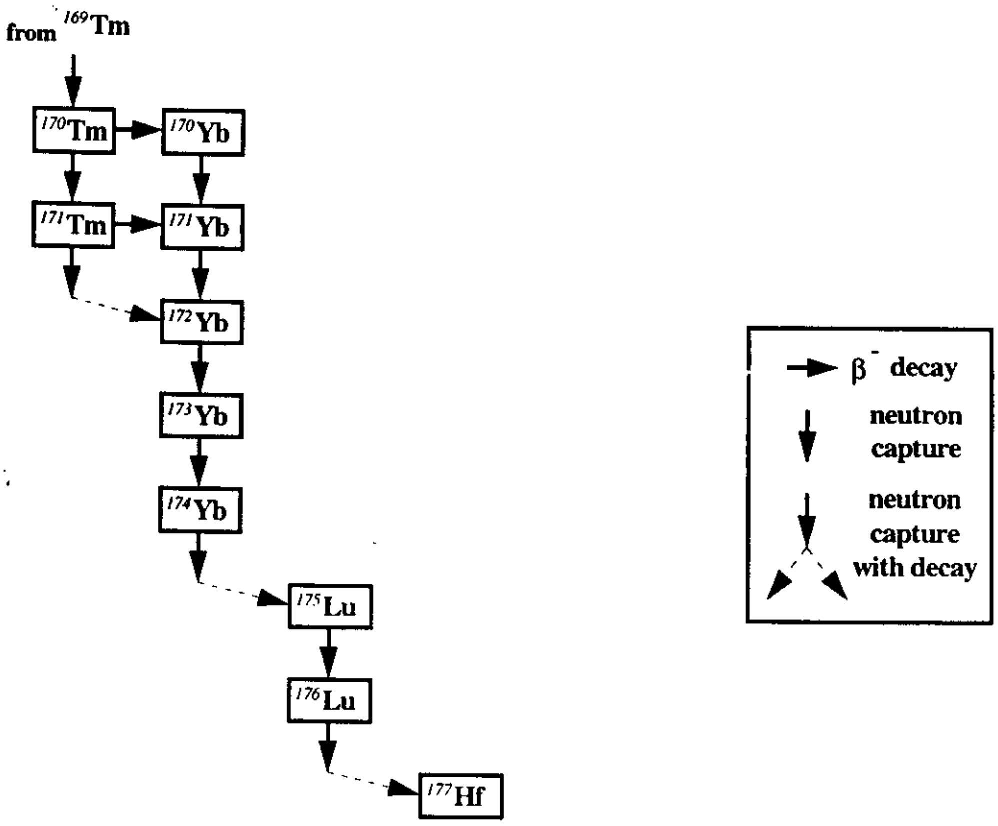
from 153Eu
154Sm
154Eu
154Gd
155Eu
155Gd
156Eu
156Gd
157Eu
157Gd
158Gd
159Gd
159Tb
160Gd
160Tb
160Dy
161Gd
161Dy
162Dy
163Dy
164Dy
165Dy
165Ho
166Ho
166Er
167Er
168Er
169Tm
to 170Tm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^{170}Tm
^{170}Yb
^{171}Tm
^{171}Yb
^{172}Yb
^{173}Yb
^{174}Yb
^{175}Lu
^{176}Lu
^{177}Hf
β^{-} decay
neutron capture
neutron capture with decay

CONCLUSION:

* The potential of LLFP (LA) incineration depends on the FUEL overall neutron production potential.

Table 1. The overall neutron production (-D) for **TRU** discharge of LWR being used in LLFP BURNERS as the fuel.

Spectrum type	$\Phi = 10^{14}$ n $cm^{-2}s^{-1}$	$\Phi = 10^{15}$ n $cm^{-2}s^{-1}$	$\Phi = 10^{16}$ n $cm^{-2}s^{-1}$	$\Phi = 10^{17}$ n $cm^{-2}s^{-1}$
	-D neutron/fission			
Fast (SPX)	**0.72**	**1.15**	**1.31**	**1.34**
Thermal (LWR-MOX)	**0.03**	**0.30**	**0.47**	**0.50**
Thermalised (CANDU)	0.21	0.43	0.53	0.60
Resonant (C.Rubbia)	0.40	0.46	0.55	0.69
Well-thermalised (Ch.Bowman)	**0.25**	**0.43**	**0.52**	**0.60**