The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1858-11

School on Physics, Technology and Applications of Accelerator Driven Systems (ADS)

19 - 30 November 2007

ADS Physics: Physics and Dynamics.
Part V

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Set IV:
OVERVIEW OF EXPECTED NICHES OF HYBRIDS in FUTURE NUCLEAR POWER: TRU-TRANSMUTATIONS and LONG-LIVE WASTE FREE OPTIONs

CONTENT

IV.1. TRU – FAST SPECTRUM ADS-BURNERS IN THE "TWO-COMPONENT NP : LWR + ADS

Fast spectrum burners are the most beneficial due to the "richness of the fuel feed" respecting incineration of both TrU and LLFP.

There are multiple scenarios which can be proposed (M.Salvatores, D.Wade et al).

Two-component NP: LWR + Burners (ADS) scenarios is one of the evident ways of ADS application.

On reactor parks with ADS- transmuters

- **Neutronics allows transmutation of MA and LLFP even in the standard critical reactors, but that there is a "price" to pay :**
-

- ***if one uses the standard LWRs, one has to increase the feed enrichment (U-235) up to very high values (~ 10 %) if transmutation of Np, Am, Cm (which are poisoning the cores) and of the selected LLFP is required.***
  This can call a negative impact on reactivity feedbacks and on intrinsic safety potential,

- ***if one uses FRs, one has to conceive a nuclear power park with a very large fraction of this type of reactors (~ 30 %), which may provide the necessary neutron surplus to handle all of the MA and LLFP.***

The use of dedicated subcritical ADS with a fast spectrum can be considered as an effective way to realise direct MA transmutation at the highest rate. It allows minimizing the park of MA transmuters

The neutron balance for a thermal spectrum is not sufficient to keep the multiplication coefficient K_{eff} close to an "economically" acceptable level ($K_{eff} \approx 0.95$), because the neutron surplus remains negative even with a very high flux level, as illustrated in Table .

Table . Neutron surplus for MA discharge : negative values indicate on the neutron deficit

K_{eff}	Reactor spectrum type	Neutron flux, n cm^{-2} s^{-1}	Neutron surplus per fission (G)
1	CANDU	10^{14}	- 0.85
	LWR	10^{14}	- 0.83
		10^{15}	- 0.44
	FR	10^{15}	0.48
0.95	CANDU	10^{14}	- 0.70
	LWR	10^{14}	- 0.69
		10^{15}	- 0.30
	FR	10^{15}	0.63

For Pu burning, MA and Tc-99, I-129, Cs-135 transmutation

three options for the nuclear power park structure can be compared :

1) PWR (UOX) + PWR (MOX) : 76 %
FR (MOX + MA + LLFP) : 24 %

FR is a fast reactor with a typical neutron surplus G $\simeq$ 0.5
which allows transmuting Tc-99, I-129 and Cs-135

The feasibility of this option should not pose problems, but detailed optimisation studies can be required

2) PWR (UOX + MOX + MA + LLFP) : 100 %
$\varepsilon_{U\text{-}235} \simeq 10$ %, $\varepsilon_{Pu} \simeq 5$ %, $\varepsilon_{MA} \simeq 3.5$ %

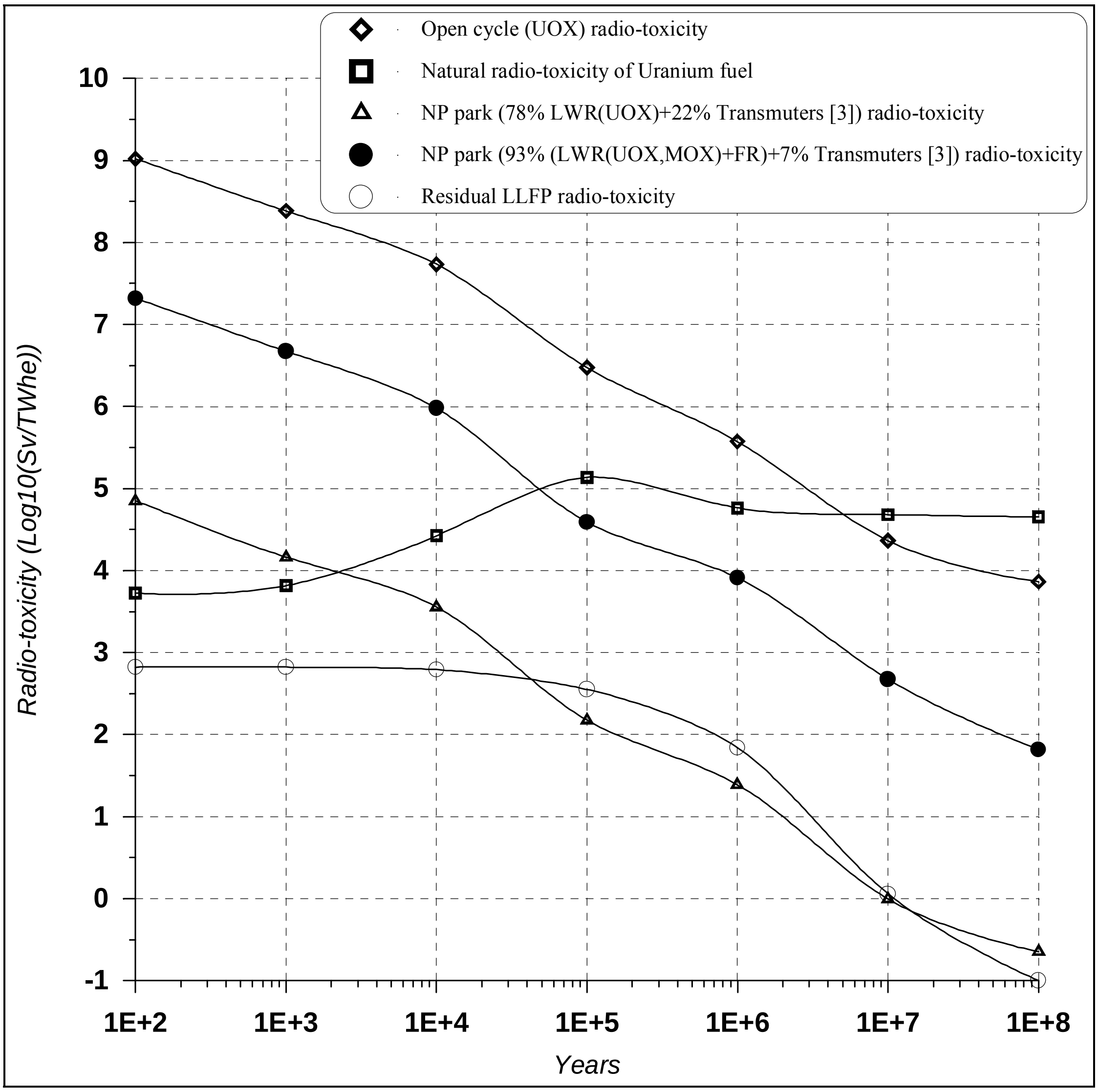
The feasibility of the core loaded with this "exotic" mixed fuel together with LLFPs, will be probably hard for clear demonstration.
In some cases, the U enrichment becomes unacceptably high.

3) PWR (UOX) + PWR (MOX) : 76 %
FR (MOX) : 18 %
ADS (MA + LLFP) : 6 %

The neutron availability in ADS ($K_{eff} \simeq 0.95$), will be sufficient to transmute three major LLFP isotopes. Expected energy spent for accelerator is relatively modest ($f \simeq 15$ %).

Such "MA and LLFP" transmuters cannot be envisaged as critical reactors (essentially for safety reasons : too small β_{eff} and Doppler effect.

The potential of toxicity reduction is presenting on Fig.



IV.2. ISFR-ADS
FOR LONG-LIVED WASTE FREE AND PROLIFERATION RESISTANT NUCLEAR POWER ("ONE COMPONENT" NP STRUCTURE)

IV.2.1. INTRODUCTION

Uncertainties in the safety and in the resistance to weapons material proliferation as well as the problems of the long-lived wastes remain the most important "painful points" of the current nuclear power.

According to IAEA analyses of the principal targets for the innovative reactor generations, the term "secure" implies primarily:

- **essential safety enhancement (firstly concerned the confident protection against severe accidents),**
- **the sure weapons material proliferation resistance as well as**
- **a significant reduction of the long-lived radiological waste sources.**

HYPOTHESES

A radical increase of the proliferation resistance can be achieved in NP based on fast reactors due to full exclusion of

- ***the fuel enrichment technology (by using the natural U/Th feed)***

NEUTRONICS OF NATURAL FUEL FED REACTORS

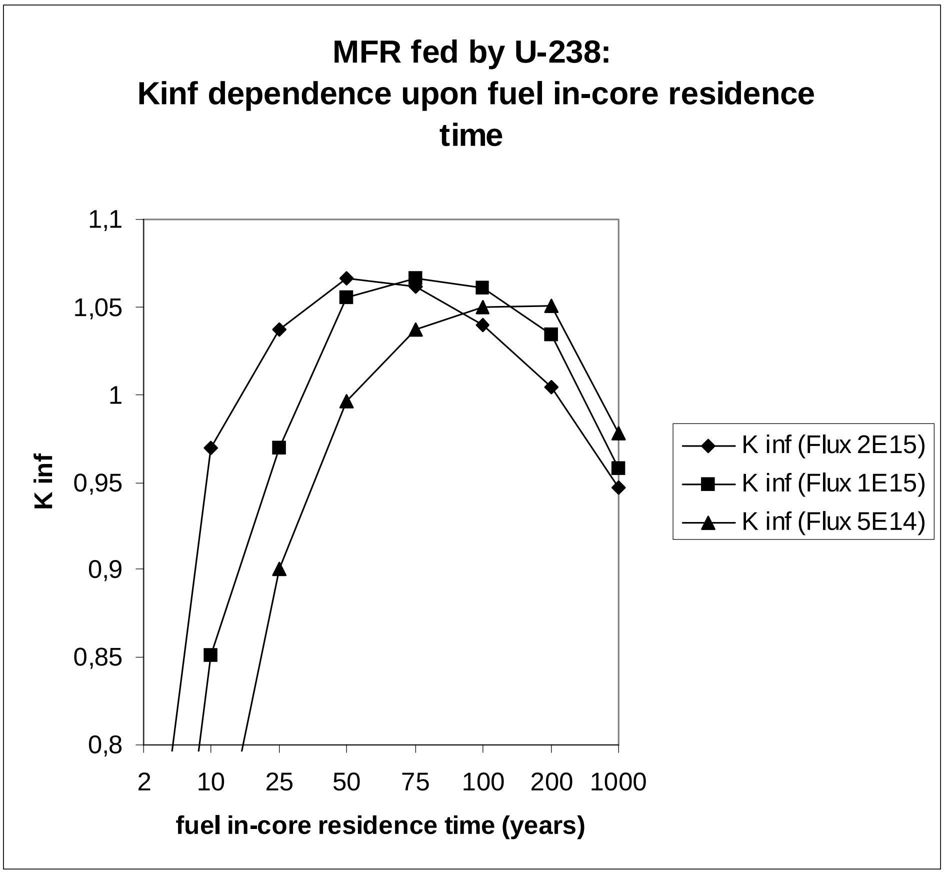


Fig. K_{inf} of the U238-fed MFR versus the fuel in-core residence time for different neutron fluxes

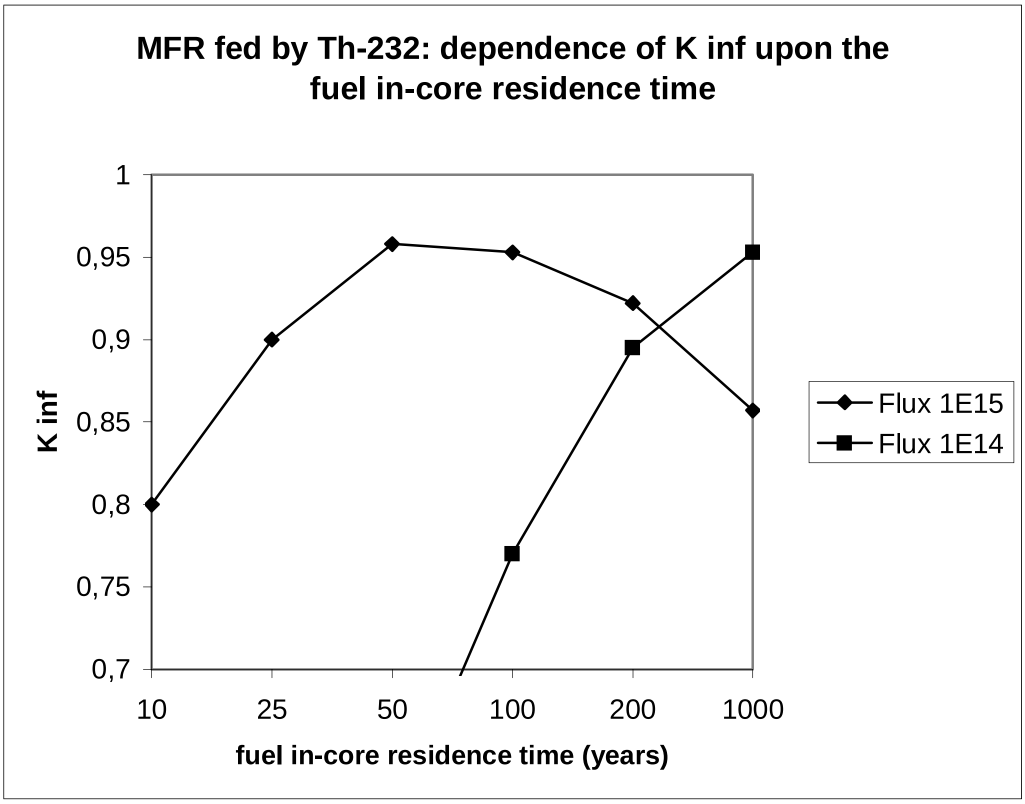


Fig. Neutron multiplication in a MFR fed by Th-232 versus fuel in-core residence time.

A radical increase of the intrinsic safety can be achieved in NP based on fast reactors due to full exclusion of

- ***the fissile-fertile isotope separation during fuel reprocessing (due the Zeroed Stable Reactivity" effect - ZSR that is almost equivalent to complete in-core fuel breeding: zeroed Internal Breeding Gain, i.e. IBG = 0) as well as suppression of the radial blankets.***

REMARKS

Respecting the long-lived waste, the most hazardous "losses" are:

- **all actinides**
  These losses appear in the form of the residual actinide + lanthanide mixtures because of their chemical semblance;

- those **long-lived toxic fission products** which may produce significant risks and require long and sure storage and permanent monitoring.

In the frame of the current separation technology, these losses may not be reduced lower than 0.1%for Pu, U and lower than 1% for minor actinide circulating masses.

The ordinary fuel cycles of fast reactors have the favourable (however, still unassuming) potential for residual actinide mass reduction compared

with the once-through cycle of current LWRs: this benefit is assessed by factor of 50-100 in magnitude.

IV.2.2. "LONG-LIVED WASTE FREE" STRATEGY

A radical increase of the waste problems can be achieved in NP based on fast reactors due to

Elimination/significant reduction of the long-lived radio-wastes during nearest millennium.

It could be quite realistic if

- ***the majority of actinides (including minor actinides) were used as a complementary fuel for energy production (as it is foreseen for the ordinary fast reactor designs and fuel cycles) and also,***
- ***the long-lived waste streams would be significantly reduced/eliminated (as in so called the "long-lived waste free strategy"). The last clause implies the following recipe:***

1. ***Those residual actinides which are contained in the mixtures with lanthanides (and can not be separated from lanthanides because of technologic limits) were "retained in the consequent (new)nuclear reactors under the neutron flux for their incineration;***
2. ***The "transmutable" toxic long-lived fission products (LLFP) which possess the favourably large neutron cross-sections and which are appropriated for irradiation under the neutron flux (like Tc-99, Zr-93, Pd-107, I-129, Cs-135), would be transmuted into the stable/short-lived nuclides;***
3. ***The "non-transmutable" LLFP which possess small cross-sections and/or which are "non-convenient" for irradiation under the neutron***

flux (like Se-79, Sr-90, Nb-94, Sn126, Cs-137, Sm-151), were permanently kept in the reflectors/blankets;

4. ***The problems with the short-lived and stable LLFP were simplified by retaining them in the interim repositories;***

5. ***The volume of the permanent repositories of the long-lived nuclides is considerably reduced and their large-scale implementation significantly postponed.***

COMMENTS

1. As known, lanthanides are not fissile nuclides and they may not be considered as the "amicable" by-components of fuels, firstly, due to their thermo-mechanical "weaknesses" at the elevated temperatures.

   To reduce the residual actinides wastes in the lanthanide-actinide mixtures, they can be gradually incinerated nearby the reactor cores at spare temperature regimes.

   At least, three questions will appear respecting fast reactor applications:

   1. **Is the non-limiting accumulation of lanthanides + residual actinides in each of fast reactors inevitable?**

   2. **Is there sufficient room in the reactors for lanthanide + residual actinide irradiation?**

   3. **Are there sufficient time as well as a reasonable neutron flux and cross-sections for significant incineration of the residual actinides?**

Non-limiting accumulation of the lanthanide + residual actinide masses is inevitable in each reactor which uses the “completely closed” fuel cycle.

To avoid such continuous accumulation, it is necessary to let nuclear reactor park grow: such growth “creates” rooms simultaneously for the new fuels (in the case of the positive breeding gain in reactors: BG>0), as well as for retention of the lanthanide + residual actinide mixtures and of LLFP, as it is shown in the fuel cycle diagram.

Even a slow (e.g. 1-3 percents per year) NP growth is sufficient for practical realization of the

“long-live waste free strategy”.

COMMENTS

Lanthanide in-reactor fractions of masses/volumes at different NP rates (doubling times). Fuel feed: U-238. The most realistic cases are marked out.

Parameters	"Semi-closed" fuel cycles with BG>0				Completely closed cycle BG=0
NP park doubling time (years)	**7**	**35**	**70**	**140**	∝
Fuel Residence Time – FRT (years)	**10**	**50**	**100**	**200**	∝
Ratio of lanthanide mass to fuel mass	**0.014**	**0.12**	**0.25**	**0.55**	∝
Volumetric fraction of La compared with in-core fuel volume (%) (conservative estimation)	**1.75**	**15**	**30**	**69**	∝

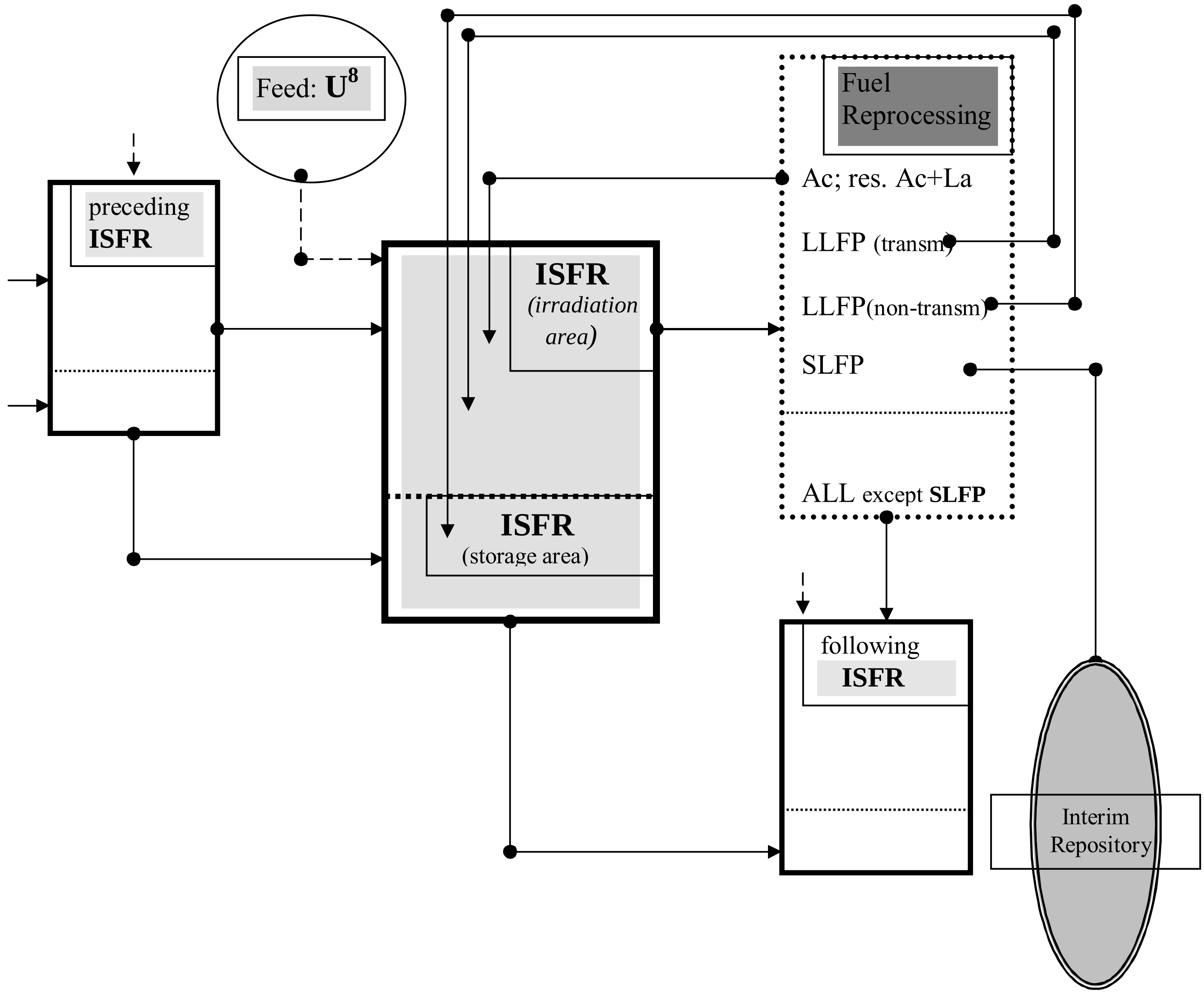
IV.2.5. FUEL CYCLE SCHEMAS

Semi-closed Fuel Cycle

The corresponding fuel cycle can be named "semi-closed" one because a part of the irradiated fuel of each reactor is discharging forever for giving birth to new "reactor chains" and, hence, leading to a reactor park exponential growth. At equilibrium, stabilization of the lanthanide + residual actinide masses in each of reactors takes place.

Majority of actinides are permanently present inside of NP park and its fuel cycles.
Fuel cycles are considered free of the long-lived actinide waste streams towards the environment due to retention of the lanthanide + residual actinide mixtures (originated in the course of fuel reprocessing) in the reactor park.

Majority of radio-toxic LLFR are also retained in the reactor park for their transmutation into stable/short lived nuclides.


Feed: U^8
preceding ISFR
ISFR (irradiation area)
ISFR (storage area)
Fuel Reprocessing
Ac; res. Ac+La
LLFP (transm)
LLFP(non-transm)
SLFP
ALL except SLFP
following ISFR
Interim Repository

The most realistic regimes refer to the "doubling times" in the range of 30-150 years.

It follows that the supplementary rooms required for the lanthanide retention are acceptable: they do not exceed 15-60 % of the core volumes. Usually, the reflector to core volume ratios are about 50% (or even bigger) in fast reactors. This is sufficient for retaining/irradiation of the lanthanide + residual actinide mixtures in such reflectors.

Meanwhile, the NP park growth necessity would provoke an important problem respecting reactor neutronics if fuel feed enrichment is forbidden (feed enrichment contradicts with the proliferation resistance strengthening target).

This growth calls reactor neutron balance worsening !!!

If the non-enriched feed is foreseen to be **used then, for the** growing NP park, the equilibrium fractions of fissile isotopes become lower compared with the completely closed cycles. Hence, their reactor neutron balance is expected to be essentially "tighter" compared with the completely closed cycle where NP park growth is not foreseen.

This worsening requires the compensation. In other words, a permanent NP growth calls for supplementary neutron generation per fuel fission in order to preserve favourable safety physics.

One may assess that, for example, transition from completely closed cycle (no NP growth) to the NP growth with the doubling time T_2 = 40 years requires roughly 0.2 n/fission supplementary to support core criticality.

As indicated above, it is utopian to require transmutation of all LLFP, primarily due to the limited neutron production per fission in the ordinary fast reactors particularly fed by natural U or Th.

However, 0.15 n/fission is only required for complete transmutation of the most radio-toxic Tc, I, and Cs nuclides. Hence, it will be quite realistic to transmute them in those fast reactor cores/reflectors where the correspondent enhancement of the neutron balance is foreseen.

The radical enhancement of fast reactor neutronics becomes the decisive factor which allows realizing this growth as demonstrated below.

IV.2.3. ON INTRINSICALLY SECURE ADS BLANKET DESIGNS

The question arises: how to meet the ambitious (mentioned above) targets in safety non-proliferation and waste management areas simultaneously?

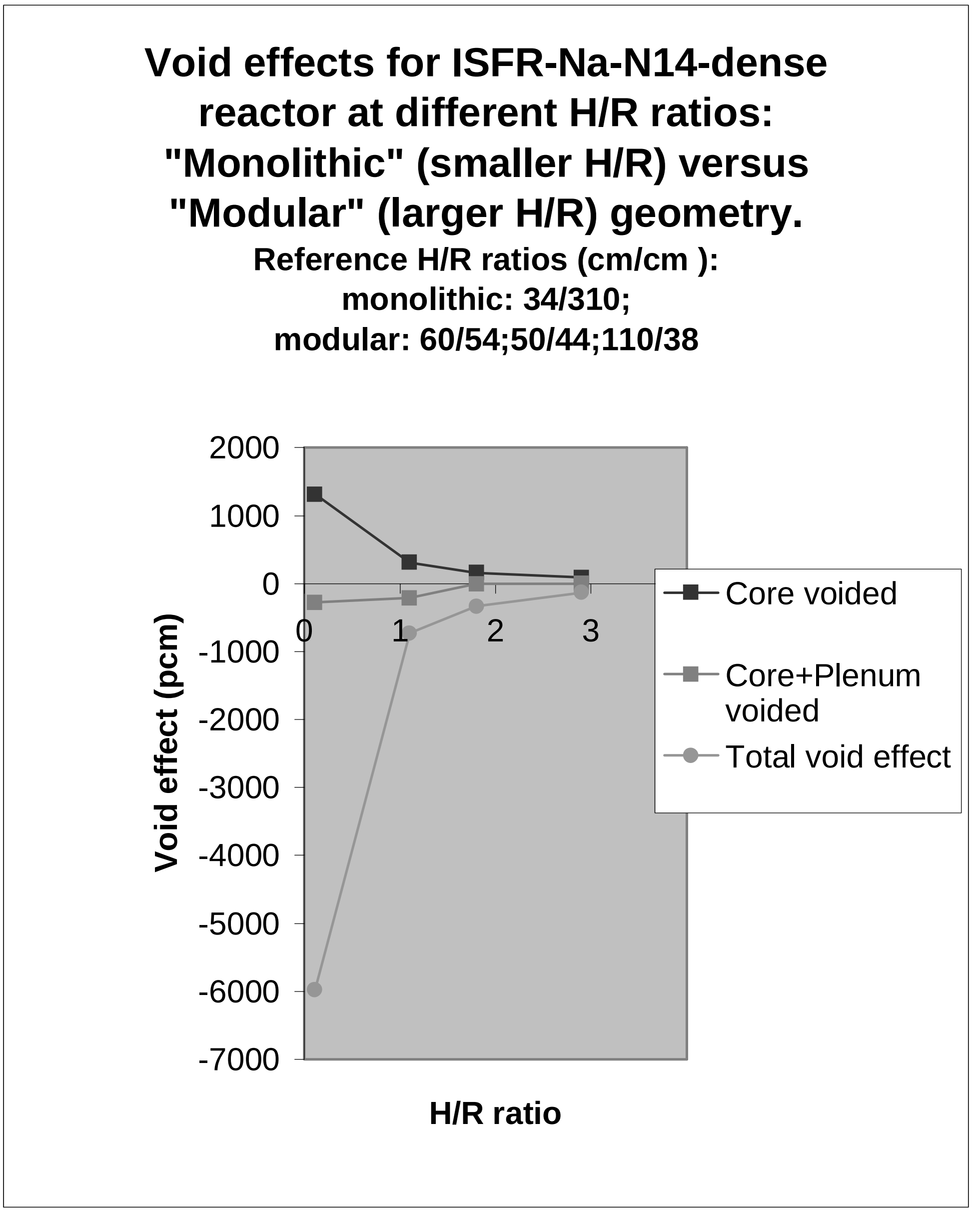
On this way, the following problems should be solved:

- *radical improvement of neutronics aimed towards -*

1. SAFETY PHYSICS

For minimization of both the reactivity margins:
Zeroed Stable Reactivity -ZSR and void effects,
a supplementary neutron net generation (compared with ordinary oxide fuelled fast reactors) is necessary.

For example, diminution of the core void effects in fast sodium cooled reactors (SPX type) requires <u>about 0.06 n/fission per each $</u> of such reduction. The multi-modular dense cores possess the most favourable intrinsic safety features respecting these effects.


Void effects for ISFR-Na-N14-dense reactor at different H/R ratios: "Monolithic" (smaller H/R) versus "Modular" (larger H/R) geometry.
Reference H/R ratios (cm/cm):
monolithic: 34/310;
modular: 60/54;50/44;110/38
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
-7000
0
1
2
3
Void effect (pcm)
H/R ratio
Core voided
Core+Plenum voided
Total void effect

2. NON-PROLIFERATION

Enhanced neutronics may allow one to design reactors possessed the ZSR feature. It permits also keeping the fissile and fertile materials non-separable.

Respecting the proliferation resistant NP, the corresponding fuel cycles should be agreed with natural U/ U-238 feeds. No radial blankets are foreseen to avoid accumulation of the easy accessible fissile materials.

3. LONG-LIVED WASTE FREE STRATEGY

As for the overall neutron balance, a supplementary neutron generation would allow one to transmute the most hazardous LLFP and to retain other LLFP inside the reactor park.

- *suppression of the long-lived actinide waste streams by means of*

1. NP GROWTH

which is indispensable for avoiding the permanent accumulation of fission products in each of working reactors. A "reasonable" NP growth rate corresponds to the NP doubling time in the range of 50÷200 years. And in its turn, a supplementary neutron generation is again required for supporting this growth.

2. LANTHANIDE + RESIDUAL ACTINIDE MIXTURE IRRADIATION UNDER A NEUTRON FLUX,

which allows one to realize simultaneously:

- the actinide waste-free regimes (no actinide waste streams) during nearest millennium due to a long NP park growth;

- significant reduction of the actinide waste masses accumulated in NP to the end of the nuclear reactor era.

Favourable ADS supplementary neutron production potential is important respecting significant increase of the overall neutron production which is quite necessary.

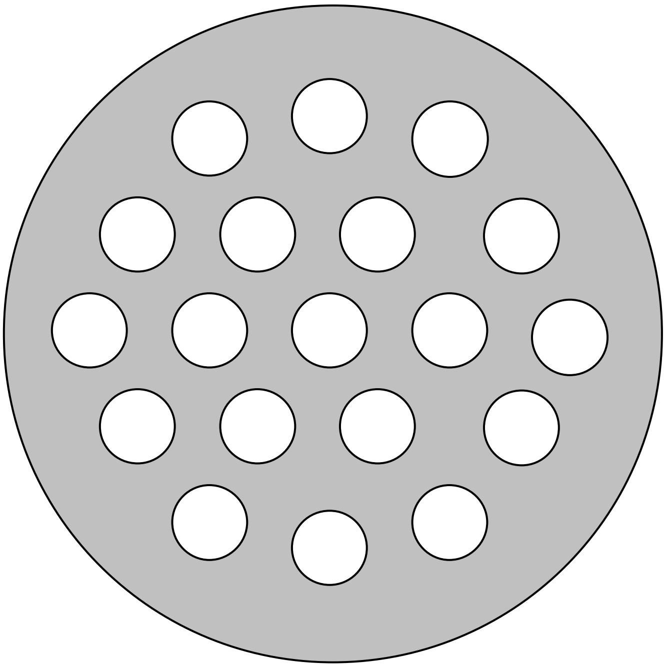
ON SUPPLEMENRARY NEUTRONIC REQUIREMENTS

Targets	*Supplementary neutron production demands neutron/fission*	*Can be met for the account of:*
"Waste free" actinide fuel cycle (suppression of the residual actinide waste streams)	Depends upon the NP growth rate. Example: **0.2 n/fis** for NP growth of about 2% per year	1. Lanthanide + residual actinide mixture retention and irradiation under the neutron fluxes in the growing reactor park 2. Core neutronics enhancement to provide a permanent NP growth
Waste free LLFP fuel cycle	**0.15 n/fis** as minimum for transmutation of the most hazardous LLFP: Tc, I, Cs	**Neutronics enhancement** (supplementary neutron production per fission)
Complementary intrinsic safety features: coolant void effect favourable corrections (if necessary)	Depends upon reactor coolant. Example: **0.2 n/fis** for sodium cooled core void effect reduction by factor of 2	**Neutronics enhancement** (supplementary neutron production per fission) + reactor's configuration optimization
Zeroed Stable Reactivity (ZSR)	Depends on reactor coolant, fuel type and core structure **0 n/fis** as minimum at zeroed core breeding gain	**Neutronics enhancement** (supplementary neutron production per fission)
Long-lived waste free strategy + higher proliferation resistance+ complementary intrinsic safety features	Totally: **0.4 – 0.5 n/fis** as minimum **ADS is very desirable for the supplementary neutron production and safety enhancement reasons**	Essential neutronics enhancement (supplementary neutron production per fission) aimed for: coolant void effect correction, ZSR, NP growth, actinide retention in fuels, LLFP + residual actinide retention and their irradiation in the growing reactor park

IV.2.4. ACTINIDE WASTE FREE ADS BLANKETS WITH FAVOURABLY CORRECTED CORE VOID EFFECTS

The careful analysis of the unprotected accidents in fast reactors confirms that, in order to achieve the deterministic-like safety levels, the anticipated reactivity insertions as well as the reactivity margins in fast reactors should not exceed roughly 1 $. It concerns primarily sodium cooled fast reactors where the temperature margins to coolant boiling are relatively small. Sodium boiling can easily provoke (in the case of a significant and positive void effect) too large reactivity insertions.

In the module reactor configuration of the ISFR-ADS, the void effects are expected to be the most favourable.



Module arrangement in a large power ADS of modular type:
a group of subcritical core-modules (SRC) embedded in a common reflector

IV.2.6. ON LONG LIVED WASTE REDUCTION

The following expression describes the fast reactor park growth of the exponential-type at equilibrium with the given doubling time T_2:

$$N(t) = N_0 \exp(\omega t), \; \omega = \frac{\ln 2}{T_2}$$

where N_0 and N (t) are the initial and the current reactor parks correspondingly.

Similar exponential-type dependence is valid for residual actinide mass accumulation:

$$A(t) = \varepsilon N(t)$$

where

ε - a coefficient which takes into account both the fraction (proportion) of lanthanides in the fission product yield and the proportion of the residual actinides in lanthanides.

Residual actinide evolution of the overall concentration $A(t)$ in the lanthanide + residual actinide mixture is roughly described by the following equation:

$$\frac{dA(t)}{dt} = \omega\varepsilon N(t) - \sigma_{ins}\Phi A(t) = \left(\omega - \sigma_{ins}\Phi\right) A(t)$$

where Φ is the average integral neutron flux.

Equation (6.1) can be applied to each of actinides and, hence, all residual actinide time-dependent concentrations can be written in a vector-matrix form.

After a long-term irradiation, the vector $\vec{A}(t)$ can be presented as:

$$\vec{A} = a(t)\vec{R}$$

where

$a(t)$ is a time dependent function and $\vec{R}$ is a normalized vector which describes the "equilibrium" proportions between actinide nuclides.

σ_{ins} may play the role of the "effective incineration effective cross-section" of the residual actinides. It can be defined as follows:

$$\sigma_{ins} \equiv \frac{\vec{E},\hat{\sigma}\vec{R}}{\vec{E},\vec{R}}$$

where

$\hat{\sigma}$ is the matrix which involves all transmutation cross-sections and fission (incineration) cross-sections of the actinide isotopes. Diagonal elements of this matrix consist of the sum of all transmutation and incineration cross-sections of nuclides,

$\vec{E}$ is the unit vector.

This actinide incineration effective cross-section σ_{ins} can be assessed by using the generalized equilibrium fuel cycle equation.

It should be mentioned that its value is sensitive to neutron spectrum hardness. For fast reactor reactors fed with natural U, it can vary in the range of 1 - 2 barns because of sufficiently large transmutation and fission cross-sections of the actinides as indicated in Table.

Table . One-group actinide cross-sections in the SPX (generalized equations of the Bateman type) at equilibrium [Salvatores (1995])

Cross-section types	Np-237	Pu-239	Pu-240	Pu-241	Pu-242	Am-241	Am-242m	Am-243	Cm-241	Cm-242	Cm-243
Transmutation	1.65	0.57	0.56	0.47	0.44	2.17	0.50	1.77	0.21	0.57	0.25
Fission	0.31	1.82	0.36	2.49	0.24	0.28	3.24	0.20	3.25	0.56	3.28
Sums	1.96	2.39	0.92	2.96	0.68	2.45	3.74	1.97	3.46	1.13	3.53

The residual actinide mass evolution (when the NP park is permanently growing) is roughly described as follows

$$A(t) \propto \exp(\omega - \sigma_{ins}\Phi)t$$

Integration over the time in the interval t = 0 ÷ T (years), where T is the time of NP growth termination, allows one to assess the total residual actinide mass (a source of the anticipated actinide pollution) taking into account the effect of residual actinide incineration.

Two options:

- the ordinary fuel cycle with the regular lanthanide removal ($\Phi \to 0$) and

- the fuel cycle with the lanthanide + residual actinide retention under a neutron flux and their irradiation ($\Phi >> 0$). The ratio of the accumulated residual actinide mass without and with such irradiation (the WR factor) shows the effectiveness of residual actinide incineration:

$$WR = \frac{\frac{1}{\omega}\left[\exp(\omega T) - 1\right]}{\frac{1}{\omega - \sigma_{ins}\Phi}\left[\exp(\omega - \sigma_{ins}\Phi)T - 1\right]}$$

Hence, the benefit from residual actinide incineration depends directly upon:

- the NP-development rate, the incineration time, the neutron flux value and

- upon the actinide incineration cross-section.

The numerical assessments can demonstrate the effectiveness of lanthanide + actinide mixture retention of in the NP park under a neutron flux.

For example, if the full in-core fuel residence time is equal to 200 years (the doubling time is correspondingly equal to 140 years) then to the end of NP growth (e.g. over T = 2000 years if NP has started with
N_0 = 1 GWe), the reactor park will be expanded up to

$$N(T = 2000y) = 10^4 GWe \,,$$

while the total U-consumption (feed + fuel inventories) will reach the value of $2.5\ 10^6$ tons.

Table . Actinide waste streams reduction effectiveness (WR-factors).

$$\omega = 0.005\frac{1}{year}; \quad \Phi - \text{var}$$

Average neutron integral flux Φ values used for waste irradiation (neutrons/cm^{2}year)	10^{14} neutrons/cm^{2}s $\times 3.15\ 10^7$ s/year	10^{15} neutrons/cm^{2}s $\times 3.15\ 10^7$ s/year
$\sigma_{ins} = 1\ barn$ (ISFR reactor with hard spectrum: near core-reflector boundary)	**$2 \cdot 10^2$**	**10^5**
$\sigma_{ins} = 2\ barn$ (SPX reactors: near core-reflector boundary)	**$4 \cdot 10^2$**	**$1.5 \cdot 10^5$**

One may conclude that there are the following advantages of both lanthanide + residual actinide and toxic LLFP incineration/transmutation under the neutron flux in fast reactors:

1. **No long-lived actinide waste streams during millenniums (the enduring "long-lived waste free" NP phase);**

2. **Retained residual actinide masses can be significantly reduced: to the end of NP-growth, this reduction is assessed roughly (see Table 6.2) as factor of $10^2 \div 10^6$ compared with the ordinary fast reactor fuel cycles;**

3. **Taking into account that the waste streams in the ordinary fast reactors are smaller compared with LWR by the factor of 10^2 in average due to fuel cycle closure, the total long lived waste mass reduction is expected to be equal $10^4 \div 10^8$ in magnitude compared with the once-through fuel cycles of LWRs;**

4. **No necessity in actinide-contained waste repositories during at least a millennium.**

IV.2.7. CONCLUSION

Intrinsically Secure Fast Reactors-ADS (ISFR-ADS) concept can be convenient for prospective NP aiming towards radically enhanced safety, proliferation resistance improvements, as well as realization of the "long-lived waste free" strategy.

Theoretically, with the ISFR park, no actinide storage in a repository is required for at least next millennium since both residual actinides and the most radio-toxic long-lived fission products can be retained and significantly incinerated/transmuted under the neutron fluxes inside the growing reactor park.

Nevertheless, long-term repositories of small size would be still required for a part of LLFP.

The considerably enhanced neutron balance (with the elevated neutron generation by about 0.5 neutrons per fission above the ordinary oxide fuelled fast reactors) is necessary to get the ISFR advantage in safety physics and in waste managements.

The NP growth requirement is fairly flexible and a "weakly" limiting factor (NP growth rate can be easily varied in the range 0.1 $\div$3 percent per year).

So, the objectives of the ISFR-ADS concept are:

- to improve the intrinsic safety characteristics;
- to enhance the proliferation resistance features;
- to reduce the accumulating actinide long-lived radioactive masses in NP park;
- to postpone the technically arduous problems of the long-lived actinide waste management up to the next millennium until appearance of more effective technologies of nuclide separation.

As it was mentioned, ISFR-ADS, particularly their modular ISFR-ADS configurations, possess the remarkable intrinsic safety features. Such modular ISFR are able to eliminate some important drawbacks of current fast reactors because they inherit:

- zeroed stable reactivity and, hence, zeroed in-core reactivity margins;
- zeroed void effects.

Moreover, there are almost zeroed long-lived actinide waste streams at least during forthcoming millennium in the case of the NP expecting growth. To the end of nuclear era, such ISFR provide significant reduction of the long-lived actinide waste masses. They are very convenient to be used as the universal "brick" for the future NP park by inheriting the important advantages (e.g. in-shop fabrication, small financial investments, series factor, the longest fuel in-core life, etc.).

As for non-proliferation features of ISFR, there are neither enriched feeds (“zeroed” feed enrichment) nor necessity in separation of fissile-fertile nuclides as well as nor radial blankets which are replaced by reflectors contained LLFP and the lanthanide-residual actinide mixtures.

GENERAL CONCLUSION:
Why Nuclear Power Needs Hybrids?

Several cases serve as the examples of reasonable applications of hybrid systems with subcritical cores:

1. A small external neutron source (unfavorable neutron production rate) could play the key role for radical enhancement of the inherent safety features for cores with degrading safety features as well as to increase deterministic safety features of traditional cores.

Example 1

The interval of core parameters providing the deterministic safety is relatively narrow and it requires searching the new technologies or "tight" core parameters (nitride fuel, limited burn-up, etc.) for the realization. Sub-criticality may expand this interval of the deterministic safety significantly and simplifies the realization of such concepts.

Example 2

Sub-criticality may restore the degraded safety characteristics of TRU/MA – transmuter core (reduced Doppler effects, unfavorable feed-back effects, smaller fraction of delayed neutrons, positive void effect) due to specifically favorable reactor dynamics.

2. Sub-criticality could play the key-role in the "concept of long lived waste free NP" (e.g. based on the application of natural fuels (U, Th) eliminating necessity of fuel enrichment /fuel reprocessing and the fuel reserve significant expansion) as well as enhancing the protection against dangerous material proliferation.

Example 4

The concept fast MSR reactors fed with liquid mobile fuels can illustrate this statement.

Several reasons advocate the application of an external source:

- **Radical enhancement of the neutron balance in cores alimenting by cheapest fuels such as the natural U and Th;**
- **Because of neutron shortage in Th feed fuels, the once-through cycle with a growth this system is impossible. The external source allows enhancing fuel breeding for new cores.**

3. The help of an external neutron source is important for problems of transmutation of long-lived wastes if only small transmuter fraction in NP park is accepted.

4. The help of the external source could be required in some new concepts: Intrinsically secure NP

BRIEFLY: ADS – GENERAL MOTIVATIONs

1. *To play a role of the effective means for radical enhancement of the inherent safety potential of cores (towards the deterministic safety level) particularly for those reactors which have degraded safety potential due to necessity to keep abundant quantities of transuraniums (actinide transmutation problems);*

2. *For realization of perspective concepts of NP,*

aiming for:

- ***elimination (significant reduction) of long-lived actinide waste;, expantion of fuel resources by direct utilization of natural fuels (U,Th) and***
- ***minimization of risks of weapons material proliferation.***
  To develop this system, the external source is required firstly to breed new cores;

3. *For optimization of NP park,*
aiming for :

- ***Minimization of the TRU transmuter park;***

- ***Minimization of LLFP transmuter park for the account of supplementary neutron production;***

If one suppose that accelerators are serving as a supplementary, however dear “control rod – like” machine, it would be not correct!

Compared with corresponding critical reactors, Hybrids may possess much more favourable safety physics and/or neutron balance and
it allows elaborating very attractive new NP concepts towards non-proliferation, long-lived waste reduction and intrinsic safety

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Reference: N° 34, issue 11 2007
Journal title: Annals of Nuclear Energy
Author: Dr. I. Slessarev

Article title: INTRINSICALLY SECURE FAST REACTORS - FOR LONG-LIVED WASTE FREE AND PROLIFERATION RESISTANT NUCLEAR POWER
Reference: ANE1797
Journal title: Annals of Nuclear Energy
Corresponding author: Dr. Igor Slessarev
First author: Dr. Igor Slessarev
Expected dispatch of proofs: 14-SEP-2007

DAPNIA-05-04-T

Université Joseph Fourier – Grenoble I

THESE

présentée par

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pour obtenir le grade de

Docteur de l'Université Joseph Fourier – Grenoble I
Spécialité : Physique

Analyse Comparative du Fonctionnement et de la Sûreté de Systèmes Sous-critiques et de Réacteurs Critiques Innovants

Date de soutenance : le 02 mai 2005

THE POWER-CURRENT FEED COUPLING IN ADS

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ADTTA meeting, Praha (1999)