

# Advanced ADS Concepts

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## 1. INTRODUCTION.

Current Nuclear Power has already proved its ability to be used as one of the principal means of the large scale energy production throughout the world.

On the current agenda, there are the list of general key-issues to which one addresses in an attempt to understand a competitiveness of NP and its niche in the whole Energetics of long-term future:

- \* economical competitiveness,
- \* long-lived waste level in connection with environmental problems,
- \* TRU further accumulation regarding political problems and public acceptance,
- \* resistance to possible proliferation of weapons grade materials,
- \* fuel resources for long-term energy production,
- \* natural safety "strategy" regarding the public acceptance of large scale nuclear energy production.

Sufficiently wide world experience of exploitation of two principal reactor types : LWR's and Sodium cooled FR's (SFRs) has revealed the following issues:

already matured LWR's (and in less extend FR's) have demonstrated ability to produce economically acceptable energy putting much less impact on environment regarding thermal and dust pollution's, CO<sub>2</sub> production than its competitors. However, there is no yet the decisive advantage of the energy production cost by LWRs (open fuel cycle, solid fuel) being compared with rivals,

Long lived radioactive waste reduction/neutralisation (both of fuels and of fission products) rest unsolved (at least, on industrial scale) problem and it demands a special attention,

PU's and MA's are accumulating with a "public frighten" rate (i.e. ~ 14 t/year in French NP),

Weapons grade proliferation menace is also important political factor particularly for American NP,

Resources of U-based fuel is not "a priori" sufficient foreseeing a long term NP development throughout the world. If one supposes that there is about 5 million tons of relatively cheap natural U for the LWR's world park of 500 GWe then these resources will be consumed in about 70 years.

Natural safety strategy [7], which can be the "non-probabilistic" warranty against the most dangerous nuclear accidents on NPPs, are not realisable neither for LWRs nor for current SFRs.

All these issues are the reasons for NP current stagnation preventing from the further NP development.

*What one could do to come this deadlock over?*

*What are tendencies in scientific and technology works which permit to go further?*

There is the widely spread opinion that many of problems can be resolved if LWR's would be able to close its fuel cycle (MOX-strategy).

Really, closure of fuel cycle (if it could be realised technically in full degree) leads to the reduction of the TRU-accumulation rate and of the most worrying long-lived fuel waste by factor of 10 - 30 and, hence, to facilitation the waste repository problems. For example, in French NP, this permits to decrease the TRU accumulation rate up to ~ 1t/year instead of current 15t/year.

However, preliminary assessment shows that in the case of LWR's fuel cycle closure:

- there will be an growth (up to 20%) of energy production cost due to fuel reprocessing necessity,
- the large scale transportation of discharged fuel will lead to a further fall of the public acceptance down,
- the maintenance of NPPs is expected to be more complicated (due to an important TRU-content in the loading fuel).

Analysis shows that one of the most important problems with MOX-type fuelled LWR exploitation is its potential safety degradation due to corresponding degradation of some principal physical parameters. Non-favourable feed back effects, delayed neutron fraction reduction, etc. lead, probably, to some important constraints in fuel multirecycling fraction.

However, if the LWR's fuel cycle closure would be even realised, other, not less important, key-issues will rest unresolved or even more aggravated such as the economical competitiveness, weapons material proliferation, fuel resources, natural safety level, etc.

Possible replacement of LWR's park by Sodium Fast Reactors (SFR) is able to change some accents in NP acceptance, however, can not change this situation drastically. Really, the potential of the waste long-term toxicity reduction is slightly favourable for SFR's than for LWRs (by the factor of 1.5 [1,2]) and this benefit is indebted mostly due to the higher fuel burnup potential of SFR's. Hence, the waste toxicity reduction factor, when SFR fuel cycle will be closed, is expecting to be in the interval 20-50 and, hence, it is slightly better than for LWRs. Nevertheless, it is important to mention that the closure of fast reactors fuel cycles does not lead to important degradation of safety physics. TRU equilibrium inventory is one of penalising factors of fast reactors: the total TRU inventory in NP, based on SFR, will be higher (roughly, by factor of 2) than for LWR based NP.

As for fuel resources, the potential of SFR's is attractive due to important fuel breeding.

Other characteristics of SFR's are less optimistic because of:

- the economic competitiveness is worse than of LWRs,
- the weapons material proliferation menace is aggravating due to higher TRU fuel content,
- the natural safety potential is not improving.

This analysis shows that widely used current reactor technology is not able to correspond to the key-issues mentioned above.

## 2. SYMBIOTIC NP STRUCTURE.

Some hopes for softening the problems mentioned above can be addressed to the approaches which are based on a symbiosis of LWR's (basic NPPs) and supplementary systems. The principal idea is to liberate LWR's from a major part of TRU's and to concentrate them in a supplementary system which is more tolerated to TRU presence to burn them out. Such a strategy is called usually the "double strata". A priori, possible disadvantage of double strata concepts relates to the problems of fuel technology development and to NPP safety.

### 2.1. LWR's + SFR's, LWR's + Sodium cooled Fast spectrum ADS (SF-ADS) [3].

In this symbiosis, one can use LWR's as the principal energy producers and SFR's - as TRU Burners. LWR's may have a "partially" closed fuel cycle (only a part of TRU is returning

back after reprocessing) and SFR's have the completely closed fuel cycle feeding by TRU's of LWR's discharge.

Facilitation of TRU management's of the LWR's park is the positive feature of this scheme. SFR's neutronics is generally less sensitive to their own TRU's produced in the closed cycle. However, if one prefers to have a minimum SFR's fraction in the NP park, then the concentration of TRU (including MA's) should be maximum : this is inevitable fate of any system devoting to TRU burning. Hence, a degradation of neutronics and safety characteristics in SFR's could be significant.

Moreover:

- Economical effectiveness of this symbiotic system is going to be worse than for LWR's based NP due to the utilisation of more expensive (compared with LWR's) fast reactors and to some supplementary efforts to restore the standard safety level.
- Reduction of TRU accumulation rate in NP is expected to be between LWR's (closed cycle, if it is real to use) and SFR's,
- The non-proliferation potential remains on the LWR's (open cycle) level,
- The total fuel resources of this system exceeds (about 30% for the account of TRU burning) of LWR's (open cycle).

It means that, regarding all principal characteristics except safety potential, this symbiosis occupies an intermediate position between LWR'(closed cycle) and SFR's (closed cycle)

The analysis (Table 1 ) of the overall neutron production of LWR' discharge shows that TRU (as a fuel) has sufficient neutronic potential to be burnt out practically in all spectra (except LWR-MOX type reactors with the standard neutron fluxes) in the critical regime . However, the final neutron balance depends also upon the "parasitic losses" in non-fuel components, upon neutron leakage and upon the burnup level ("parasitic" neutron capture in fission products). The special code [1,10] for evaluation of the neutron consumption/production potential of fuels at equilibrium state has been created.

Table 1. The overall neutron production (-D) for TRU discharge of LWR being transmuted in different neutron spectra and fluxes

Spectrum type	$\Phi = 10^{14}$ n cm <sup>-2</sup> s <sup>-1</sup>	$\Phi = 10^{15}$ n cm <sup>-2</sup> s <sup>-1</sup>	$\Phi = 10^{16}$ n cm <sup>-2</sup> s <sup>-1</sup>	$\Phi = 10^{17}$ n cm <sup>-2</sup> s <sup>-1</sup>
	-D n/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

Safety potential of subcritical Burner versions (SF-ADS) could be essentially improved. However, it leads to some economical penalties due to the necessity of accelerator technology. Moreover, the natural safety of all NPP park will be limited by a low LWR's natural safety potential.

## 2.2. LWR's + "DEVOTED" SYSTEMS ON THE BASE OF INNOVATIVE TECHNOLOGIES.

Several innovative concepts are widely discussing now [4-6] for practical realisation.

### 2.2.1. LWR's + TRU Burners (ADS TIER-1) by Dr. Ch. BOWMAN [4] with molten salt fuel and well-thermalised neutron spectrum

The basic idea (there are several options) is to dissolve TRU's of LWR's discharge in a fluoride molten salt (Oak Ridge type) together with Zr-cladding and with all fission products-FP (separated from fertile material). This fuel will be surrounded by the C-moderator and has to work in once-through regime with a high average FP-concentration being continuously fed by TRU's together with fission products. Such a feed will be created after separation of U-238 from LWR's discharge.

Despite TRU important concentration, the unusually high FP-concentration level leads to important poisoning and to reduction of the neutron multiplication potential. Hence, the subcritical regime is compulsory. There is still some doubts in neutronics feasibility of this concepts.

Calculations show that (comparing with LWR's discharge) the concentration of PUs is reducing by factor of 5 and the concentrations of MA's are not changing much. It means that the total fuel waste toxicity reduction factor can not exceed 10 being compared with current LWR's.

Attractive features of this concept are:

- Liberation of LWR's from necessity of the MOX fuel application,
- Simplification of TRU-Burner fuel cycle,
- The high natural safety potential of TRU-Burners due to subcriticality and to the stable reactivity,
- The important reduction of TRU's discharge mass in TRU-Burners due to the high burnup; significant reduction of irradiated fuel transportation.

The most important beneficial feature of this concept is the growth of the proliferation resistance: a separation TRU and FP is not envisaged neither for LWR's discharge nor for a TRU-Burner system.

Drawbacks could be also essential:

- The level of MA's in wastes is not reducing,
- There is no sufficient fuel reserve benefit for future NP,
- The total natural safety potential of NP is limited by LWR's and, hence, is not essentially improving.

### 2.2.2. LWR's + TRU Burners (RBR) by C.RUBBIA [5] with HTR-type of fuel and the Resonant neutron spectrum.

Recently, the innovative concept of the TRU-Burner on the base of HTR technology has been proposed, taking into account a significant potential of HTR type fuel to keep an extremely high burnup.

Prof. C.Rubbia proposes to achieve an extraordinary high maximum TRU-burnup ( $B_{\max} \sim$  up to 99.9% of h.a.) in the once-through fuel cycle using the pebble-bed technology and low concentrations of TRU's located in almost non-neutron consuming graphite matrices.

The principal reason of application of TRU-Burners coincides with the Ch.Bowman's concept, but here is the special accent on the application of the "pure" (separated from FP and Uraniums) TRU-fuel with the "deep" burnout in once-through cycle and in "Resonance" spectrum which involves "sleeping" PUs and MA's nuclides such as (Pu-240,242, Am-241, 243, etc.) in the intensive transmutation process. It could be realised if one can create such a neutron spectrum where maximum neutron density is concentrating around TRU resonance's. It leads to sweeping of these "sleeping" isotopes to "active" ones with elevated neutronic reaction rates.

As in Ch.Bowman's idea, C.Rubbia "simplifies" fuel cycle for TRU-Burners and proposes the subcritical regime allowing to get the maximum margin of neutron surplus production to achieve the maximum burnup and to overcome problems with TRU-Burner safety.

As it was already mentioned, the level of long-lived TRU wastes is roughly inversely proportional to the maximum TRU's burnup ( $B_{max}$ ). Meanwhile, the  $K_{eff}$  is defined by the average fuel burnup ( $B_{av}$ ) value in the TRU-Burner. The assessments show that one should reach  $B_{av} \approx 0.85\%$  to have  $B_{max} \approx 0.999\%$ . Hence, subcriticality has to be essential.

The detailed analysis confirms the extremely high sensibility of waste mass to the average burnup (and, hence, to the chosen  $K_{eff}$  level). This explains why, subcriticality provides an important advantage in TRU waste reduction.

Due to potentially high burnup in TRU-Burners and reduced wastes (after separation TRU and U+ FP of LWR's discharge), the total fuel waste reduction factor is expected to be sufficiently large (about  $10^3$ ), which supply this concept with a definite attractiveness.

"Wakening" of the "sleeping" nuclides has a sense, if toxicity of "fissionable" TRU is essentially lower than "sleeping" ones as in the case of Pu-239 compared with Am-241, Am-243, Cm-242, 244. If not, any thermalised spectrum provides similar effect of toxicity reduction depending mostly on TRU burnup.

General problems of this concept are the following:

- economical competitiveness is going to be questionable due to important subcriticality level (because a significantly high burnup is required),
- natural safety as well as non-proliferation potentials are defining by LWR's park and can not be enhanced radically in the frame of this concept,
- the total fuel reserves for future NP are not increasing essentially.

### 2.2.3. LWR's + MA-Burners ("double stratum") [3]

Another version of NP fuel cycle can also be considered, when TRU's of LWR's discharge are subdivided on two parts via the separation technology application: one is MA's and another is PU's. PU's can be recycled in LWR's or/and FR critical reactors, while MA's can be transmuted in the devoted MA's-Burners where MA's concentration will be dominant. Such approach allows to reduce a negative impact of MA's on LWR's/ FR's safety and to minimise the fraction of MA's (down to 7%) in the total reactor park. An important concentration of MA's in the fuel leads to problems of safety physics of MA's-Burners and the subcritical regimes can be recommended to overcome these difficulties. Moreover, MA's have a very "tight" neutronics and fast or well thermalised spectra are the only candidates for MA-fuels to be used with (see Table 2).

Table 2. The neutron production -D neutron/fission for MA's part of LWR's-discharge being transmuted in different neutron spectra and fluxes

Spectrum type	$\Phi = 10^{14}$ n cm <sup>-2</sup> s <sup>-1</sup>	$\Phi = 10^{15}$ n cm <sup>-2</sup> s <sup>-1</sup>	$\Phi = 10^{16}$ n cm <sup>-2</sup> s <sup>-1</sup>	$\Phi = 10^{17}$ n cm <sup>-2</sup> s <sup>-1</sup>
Fast (SPX)	0.07	0.65	0.87	0.94
Thermal (LWR-MOX)	-0.76	-0.37	-0.23	0.01
Thermalised (CANDU-type)	-0.77	-0.43	0.11	0.55
Resonant (C.Rubbia)	-0.44	-0.16	0.31	0.45
Well-thermalised (Ch.Bowman)	-0.77	-0.37	0.29	0.57

Fuel waste toxicity level of "double strata" concepts is defined by their principal components: LWR's, SFR's critical reactors (if any) and MA's-Burners.

If the current separation technology together with the standard reactor technology are applied then one can envisage about one/two orders of the toxicity reduction factor compared with LWR's (open fuel cycle).

General properties of the "double strata" approach is quite similar to all symbiotic systems, however, complication of all Nuclear Power structure and current reprocessing modest potential are not able to create a "breakthrough" step in NP's renaissance.

Regarding Symbiotic systems, one can conclude:

*Symbiotic Systems, based on matured LWR's technology and the currently used reprocessing technology for TRU's burning, are able to reduce the PU accumulation rate as well as fuel the waste long-term toxicity by the factor of one-two orders compared with current park of LWR's (open fuel cycle). There is some hope to enhance some non-proliferation characteristics (particularly, for Ch.Bowman's concept). However, these are the only important benefits of Symbiotic systems. Unfortunately, the use of symbiotic systems leads to NP structure complexity. Development of new subcritical TRU-Burners and TRU fuels is required presumably. As result, one is expecting to loosen the current economic competitiveness of NP further on.*

*There is still the long list of problems which are waiting for their resolution. Among them:*

- limited fuel resources regarding long future,
- problems with weapons material proliferation (except presumably the Bowman's concept),
- a low natural safety potential.

As result, regarding NP renaissance, the general conclusion seems to be very gloomy: there is no clear hope to enhance radically the NP position in economics, long-term fuel resources and safety, except a partial (although important) reduction of the fuel waste mass and their toxicity.



### 3. MONO - STRATUM CONCEPTS AMONG EMERGING TECHNOLOGIES

#### 3.1. The "ENERGY AMPLIFIER" (EA) by C.RUBBIA [8].

The approach of the "reduced production of TRU and burnout of already accumulated TRU" has been realised in the concept of the Energy Amplifier proposed by Prof. C.Rubbia.

It is known that Th-based fuel family (for both closed cycle and once-through cycle) consists mostly of uraniums (please, compare Fig. 3.1 and Fig.3.2) and, in much less degree, of TRU's. Hence, for both cases, waste toxicities can be reduced considerably. However, the long-lived toxicity of the two principal nuclides: U-233 and U-234 is not negligible and plays an important role (compared with other nuclides) since  $\sim 10^3$  years after fuel irradiation. Neutron balance tightness is overcome by means of an external spallation (ADS) source (subcritical regime is foreseen).

The EA inherits the traditional fuel element design (the solid "non-mobile" fuel concept), as well, it uses the innovative coolant technology (liquid Pb). There was no idea to "design" the "natural safety" in whole extent to protect the EA against all heavy ATWS (like in the BREST concept), however, the subcritical regime allows to avoid the most severe TOPWS accidents at least.

The EA is working with closed fuel cycle and with the burnup level which is typical for fast critical reactors.

*The most important privilege of the EA is the significant reduction of the waste toxicity*, particularly inside of the interval  $10^2 - 10^3$  years after irradiation (the factor of 2-4 orders in the magnitude) compared with current LWR's. It is expected that the accelerator cost will not put an important penalty in the EA economics if a "modest" subcriticality ( $K_{\text{eff}} = 0.96-0.98$ ) level is used to enhance safety.

The use of Th fuel with considerable breeding expands fuel resources in a great extent - by the factor of 3 orders in the magnitude.

Several factors testify that there are some doubts regarding practical EA applications:

- Economic competitiveness has to be clarified: it requires to pay for an accelerator, for energy of the proton beam supply; no simplifications of the fuel cycle and of the reactor design are envisaged,
- Proliferation problems require the definite attention: a separation of U's from FP leads to a menace of the non-authorized use of the U-fuel, although the elevated concentrations of U-232 and Pa-231 create a supplementary protection barrier.

Because of there is no technology of closed Th cycle yet, non-negligible strengths are required to mature it.

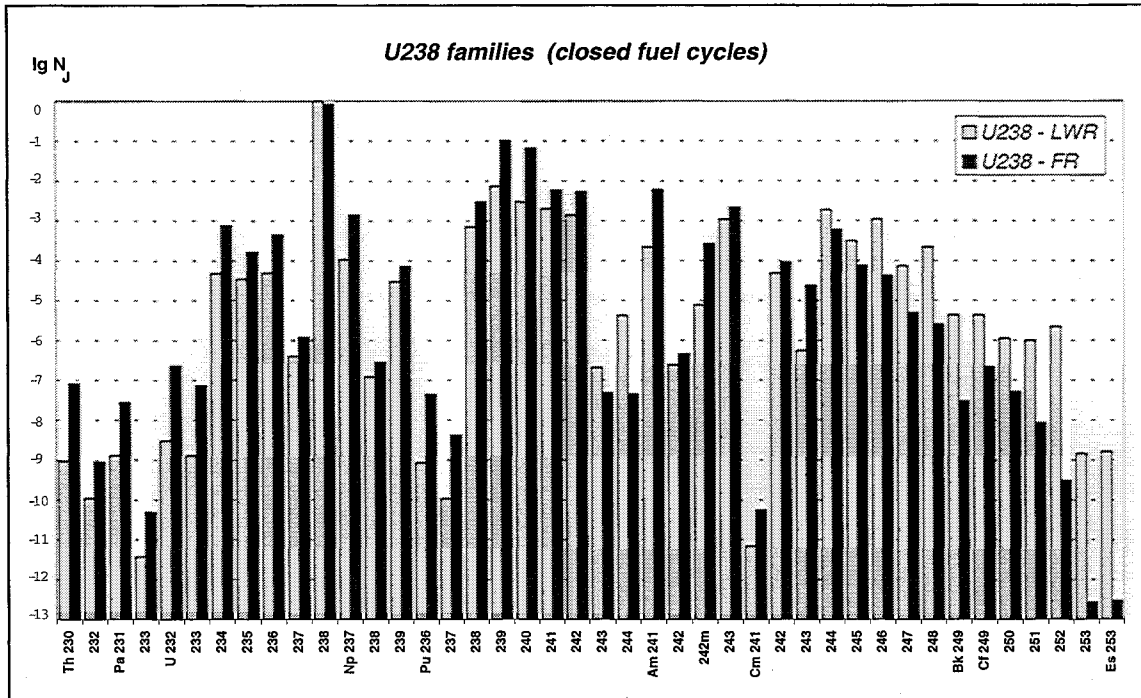


Figure 3.1.  $^{238}\text{U}$  family normalised concentrations  $N_j$  ( $\sum_j N_j = I$ ) at equilibrium when irradiated in two different spectrum types (Light Water Reactors and Fast Reactors).

### 3.2. The "TASSE" - Thorium based Accelerator driven Subcritical System for Energy production (CEA [9])

Initially, this concept was born as an attempt to simplify the expensive and worrisome fuel recycling, reactor designs, its safety means for the account of the elimination of the fuel enrichment and (is it is feasible) irradiated fuel reprocessing. A radical expansion of fuel reserves towards to a radical enhancement of NP economics and a waste toxicity reduction were also foreseen.

One of the most important features of the TASSE concept is the "equilibrium regime" of the fuel and FP concentrations.

An "equilibrium state" of the fuel isotope concentrations - "equilibrium vector" (see, for example, Fig. 3.2) is forming when the all "repeating" processes of the fuel "management" such as:

- fuel feed by a combination (a "vector") of "father - nuclides",
  - transmutation of this "vector" under a neutron flux and due to radioactive decays,
  - irradiated fuel "vector" discharge and,
  - return of the "reprocessed fuel vector"
- have a continuous time-behaviour.

This equilibrium fuel concentration vector (being created for every "father"-nuclide and is calling father's "family") depends mostly on neutron spectrum type and neutron flux level.

If one of these processes has a "step-wise" behaviour (as in the case of the "batched" reloading typical for a solid fuel), one can achieve a "quasi-equilibrium" state of cores with the reactivity swings. It means, that only "mobile" fuel concepts have a potential to approach closely to "equilibrium state" thus supporting a "constant" reactivity during fuel burn-up, which is extremely important for both exploitation and nuclear safety.

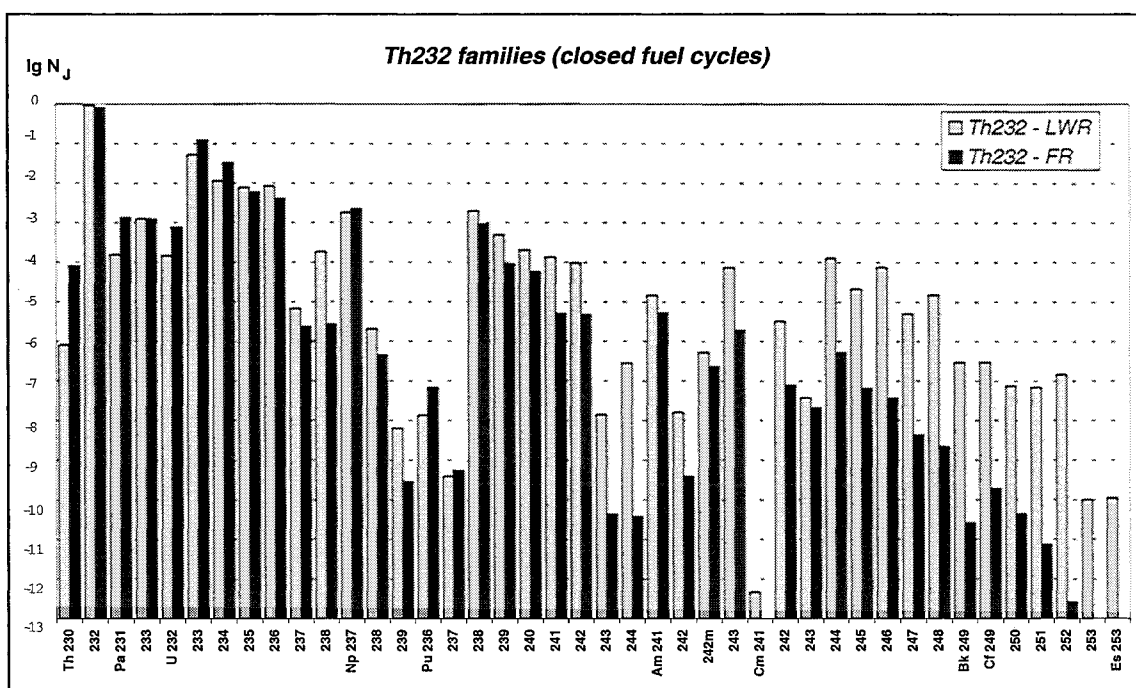


Figure 3.2.  $^{232}\text{Th}$  family normalised concentrations  $N_j$  ( $\sum_j N_j = 1$ ) at equilibrium when irradiated in two different spectrum types (Light Water Reactors and Fast Reactors).

The following set of key-ideas was served as the background of the TASSE:

- The cheapest (non - enriched) and low toxic fuel, practically, without TRU's production,
- The high fuel burn-up level,
- The "mobile" fuel concept,
- The subcritical core with a supplementary external source (ADS type),
- Once-through cycle (or simplified "on line" reprocessing) to avoid a long-term fuel cooling and significant transportation of the irradiated fuel masses,
- An optimised burn-up level to facilitate the proton current requirement.

All initial versions of the TASSE are aiming to use *natural Th* because it has the lowest toxicity after irradiation [10] due to a negligible accumulation of TRU's, to expand natural reserves, to gain in non-proliferation and natural safety potentials.

A high burnup level is very important particularly for once-through cycle because it (together with a low toxic fuel) reduces the level of the waste toxicity. For once-through cycle,  $K_{\text{eff}}$  level is particularly sensitive to burnup because a part of fuel is losing. For closed cycles, a high burnup is also important because it leads to minimisation of both reprocessing volume and wastes.

"Mobile" fuel concept (i.e. liquid, pebble-bed fuel or similar "circulating" fuel) allows to achieve the highest level of the average fuel burnup (in this case the average fuel burnup is close to maximum one and, hence, both minimum waste and the best neutron economy are expected) as well as to avoid reactivity swings during the fuel evolution.

Subcritical regime is attractive because of two basic reasons:

\* For enhancement of the neutron surplus production by a fuel because this surplus is rather modest if natural Th or U is used in all neutron spectra. This is important for realisation of once-through cycle suffering from a neutronics tightness;

\* To overcome difficulties with a limited safety potential regarding the reduction of the effective delayed neutron yield if circulating molten salts are going to be used. A natural resistance to all principal dangerous ATWS allows to move towards a natural safe system [11].

Simplicity of front and end back of the fuel cycle is the radical means to achieve the best economics and to have the acceptable public opinion.

Two types of fuel cycles were studied for the TASSE:

\* once-through cycle as the most simple which does not require neither fuel enrichment nor the fuel recycling technology and

\* closed cycle with a simplified reprocessing technology "on line" in the case of strong neutronics constraints to realise once-through cycle.

As it was mentioned, optimisation of the burnup level at equilibrium is important for a choice of the best neutronics. Low equilibrium burnup leads to insufficient accumulation of fissionable nuclides (such as U-233). On the contrary, too high burnup leads to the core poisoning by FP and to the more important fraction of the highest U isotopes and TRU. This transition decreases the neutron surplus.

Regarding neutronics constraints, one can confirm (see Table 3.1) the sufficient potential (the neutron surplus does exceed  $0.25n/\text{fission}$ , which would be equivalent to  $K_{\infty} > 1$  if there is negligible parasitic neutron captures), to work at near critical conditions at "closed cycle equilibrium" for the following neutron spectra:

\* fast spectrum (similar to SPX) for both natural Th and U feed,

\* thermal, thermalised and well-thermalised (with the fuel to C-moderator ratio is about 1:1000 or higher) spectra with Th-232 feed. On the contrary, U-238 is losing its capability of the sufficient neutron surplus production.

The neutron surplus production for Th based fuel is very much sensitive to the neutron spectrum hardness because the important members of Th-family such as Th-232 and U-234 have thresholds of fission in the vicinity of several MeV. In this case, any means of neutron spectrum hardening can be beneficial.

The initial fuel inventories of TASSE's can be created by the accumulated TRU's. When TASSE launching, Th-232 will be used as the feed. After some "transition period", the TASSE's fuel is approaching to its equilibrium state when TRU nuclides are gradually vanishing down to their equilibrium content. For the once-through molten salt fuel cycle, no fuel waste during this transition is foreseen. The last conclusion can be considered as the one of the important specific features of liquid fuel (i.e. molten salt) systems.

Really, if such a system is able to work in the once-through fuel cycle at equilibrium then its discharge can be used directly (without treatments) in similar system fuel inventory. In

this case, no wastes (regarding those wastes which appear as a results on irradiated fuel reprocessing) are envisaged.

Preliminary overall neutronics study shows that:

1. Fluoride fuel salts (without moderators) create, so called, the "fast-intermediate" neutron spectrum: due to inevitable elevated concentrations of light nuclides and an important inelastic cross-sections of F, neutron spectrum is shifting from the "standard" fast towards intermediate one, resulting in an important loss of the neutron production potential (0.1 n/fission less when compared with SPX-spectrum). The corresponding decrease in  $K_{\infty}$  is assessed as about 0.04 for both U and Th based fuel. A non-compensated loss of fuel in the equilibrium once-through cycle (due to fuel continuous discharge) leads to the loss of about 0.3n/fission (at burnup ~ 40%). As result, the total loss of the fuel neutron production for once-through fuel cycle is equal to ~ 0.4 n/fission and the optimum  $K_{\infty}$  value is expected to be ~0.9. This requires an intensive external source in the TASSE core to work.
2. Chloride salts conserve a sufficiently hard spectrum [9] (similar to SPX). However, the natural Cl consumes a significant number of neutrons (about 0.25n/fission). As result, the total values of the neutron production for fluoride and chloride salts are assessed as similar. Replacement of the natural Cl by its less neutron consuming isotope - Cl-37 can be proposed for neutronics enhancement.

The important reduction of the neutron production in once-through cycle can be considered as a penalty for the simplification of fuel cycle. In other words, there is the following alternative on the agenda :

either to apply

*the most simple fuel cycle (no enrichment, no irradiated fuel recycling) with an intensive external source*

or to use

*a fuel cycle with total/partial recycling of irradiated fuel in an attempt to reduce the intensity of the external source down to an acceptable level.*

As it was mentioned, the molten salt once-through cycle option of the TASSE has an essential neutronics tightness: a reduction of the neutron production due to the "homogenised" non-compensated discharge. It means that the continuous "homogenised" fuel discharge includes a "fresh" part of the fuel decreasing its capacity. This disadvantage is compensating by the ability to use this discharge directly for the initial inventory of a new TASSE. In this case, the growth of the nuclear power park with the "doubling time" of about 30-40 years can be realised. Moreover, during transition time, when TASSE's use TRU fuel, there will be no wastes in NP at all.

Table 3.1. The overall neutron production (-D) of Th-232/U-238 based fuel closed cycles

Spectrum type	$\Phi = 10^{13}$ n cm <sup>-2</sup> s <sup>-1</sup>	$\Phi = 10^{14}$ n cm <sup>-2</sup> s <sup>-1</sup>	$\Phi = 10^{15}$ n cm <sup>-2</sup> s <sup>-1</sup>	$\Phi = 10^{16}$ n cm <sup>-2</sup> s <sup>-1</sup>
	-D neutron/fission			
Fast (SPX)	0.36/0.37	0.36/0.49	0.36/0.62	0.30/0.66
Thermal (LWR-UOX)	0.19/-0.53	0.17/-0.09	0.01/0	-0.86/-0.04
Thermalised (CANDU,UOX)	0.26/-0.26	0.25/0	0.13/0.07	-0.60/0.02
Resonant (C.Rubbia)	-0.12/-0.38	-0.68/-0.24	-2.18/-0.39	-3.05/-1.11
Well-thermalised (Ch.Bowman)	0.24/-0.41	0.22/-0.19	0.02/-0.14	-0.99/-0.19

The "optimal" transitory to NP with TASSE park (which is co-ordinated with a time margin needed for development of reprocessing and accelerator technologies) can be foreseen as the following stages:

- "Transitory stage": burning TRU in the TASSEs (TRU + Th fuel) to accumulate "Th-based equilibrium" fuel. Once-through cycle (no reprocessing) and relatively modest subcriticality (small power accelerators) can be applied due to excellent TRU neutronics. During this stage, current LWR are replaced by TASSEs, no total NP park growth is envisaged.
- "Long-term stage": equilibrium Th-based cycle with fuel recycling ("On-line" reprocessing technology is required for best economics and waste reduction) and again the modest subcriticality (small power accelerators) is sufficient.

If an important temporary/permanent growth of NP power is required, then "once-through fuel cycle (or partial fuel recycling scheme) can be applied. However, either more powerful accelerators will be required or U-235 enriched fuel reserves can be used without any risk to increase waste toxicity (no waste is foreseen),

One of the specific attractive features of the molten salt fuelled TASSE concept is the following:

*During all stages of NP development, no essential radioactive waste is expected to be produced by TASSE. Beginning with the Long-term stage, NP will produce negligible masses of wastes.*

There is another radical way for maximising  $K_{\text{eff}}$  for once-through cycle: to discharge the fuel with the highest burnup only. It can be naturally realised by using the pebble-bed fuel type (resting in the frame of the concept "Mobile fuel"). Developing a technology of distinguishing fuel balls in the accordance with its burnup level, one can discharge the "most burned" pebble beds. As a result,  $K_{\text{eff}}$  will improve, however, the "self-reproduction" of TASSE's fuel will not be possible.

For fast hard spectrum, the fuel can be fabricated in a shape of small (about 10 mm in diameter) balls of solid thorium coated by either stainless steel or vanadium (or other resistant materials like C-layers). He or Pb or salts (without fuel) can be used as coolants. The last two coolants are much suited for ADS application: there is no pressure (except static one) inside of a reactor vessel.

Evidently, molten salt fuel is more suitable when reprocessing is foreseen to be used. Pebble bed fuel is more correspondent (at least now) to once-through cycle application.

### 3.3. Synergetic: the preliminary inter-comparison analysis.

Analysis shows that all these innovative concept define some "field" of niches where they are not overlapping completely, however, neighbouring closely each other. This field can allow to make a proper choice of a concept which is more suitable regarding all technologic, industrial or political constraints.

Some versions of the TASSE concept, for example, are closely related to the AMSTER [6] if one replace the natural Th-fuel feed by the enriched Uranium fuel, moving towards the critical working regime and to the fuel cycle closure. Such a version seems to be more conservative and matured, however, it loses the desirable simplicity of the fuel cycle (particularly, due to U-236 separation necessity), fuel resource and the natural safety potentials.

At the same time, TASSE with well-thermalised spectrum (CANDU-type) and closed natural Th-fuel cycle is approaching to the known MSRE critical reactor, excluding the necessity of fuel enrichment and the critical regime applications.

The TASSE is approaching to the EA-concept, if one uses closed Th-fuel cycle (there is no experience yet in this domain), solid (non-circulating) fuel technology, thus, losing fuel cycle simplicity and, probably, decreasing the natural safety potential.

One can conclude that innovative technologies and approaches such as:  
*natural Thorium combined with TRU (in the early transitory stage) and Th based "equilibrium" fuel (in long-term stage) with a simplified fuel cycle, subcritical (ADS type) regime of work, mobile fuel and simplified core designs, "up building" of the natural safety strategy,*  
 are seemed to be able  
*to expand significantly the capability of future NP attaining all key-goals and to move the majority of NP weaknesses away in the competition with the alternative sources of energy.*

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**ANNEX 2 . Preliminary Electricity Production Cost (% of the current cost)  
Inter-Comparison : LWR versus TASSE**

	LWR's	TASSE's (once-through cycle)	TASSE's (closed cycle)	Comments
Capital cost	80	<~ 80	<~ 80	TASSE's have a potential of design simplification
Current Fuel cost	20	factor of 10 * ~0	factor of 3 * ~1	⇐ feed masse reductions, ⇐ fuel cost reduction (*)
Fuel recycling, waste management's	20	factor of 10 fuel discharge repository only ~2	factor of 3 simplification of reprocessing technology ~5	⇐ discharge mass reduction
Acceptable ADS-technology + energy consumption cost	-	~ 40	~ 35	An important margin for ADS technology expenditure
Total current cost	120	120	120	Equal <i>current</i> cost is postulated
		> 1000 ↑↑ ~ 20 ↑	> 1000 ↑ >1000 ↑	Supplementary advantages: Fuel reserves growth factor Proliferation resistance Fuel waste toxicity reduction factor Natural safety strategy