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SMR/1220-23

Workshop on

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

13 March - 14 April 2000

*Miramare - Trieste, Italy*

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# Advanced ADS Concepts

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Workshop on Nuclear Reaction Data and Nuclear Reactors
Trieste 14 April 2000

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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, $CO_2$ 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 inevitable 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 factor if one takes into account that the closure of fast reactors fuel cycles does not lead to important degradation's 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.

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.

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

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, 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 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 rests on the LWR's (open cycle) level,
- Total fuel resources of this system exceeds (about 30% for the account of TRU burning) of LWR's (open cycle),

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

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 non-fuel components, neutron leakage and the burnup level.

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 $cm^{-2}s^{-1}$ | $\Phi = 10^{15}$ n $cm^{-2}s^{-1}$ | $\Phi = 10^{16}$ n $cm^{-2}s^{-1}$ | $\Phi = 10^{17}$ n $cm^{-2}s^{-1}$ |
|---|---|---|---|---|
| | -D 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 + THE "DEVOTED" SYSTEMS ON THE BASE OF OTHER TECHNOLOGIES.

Several concepts are widely discussing now [4-6] for practical realisation. Among them:

### 2.2.1. LWR's + TRU Burners (ADS TIER-1) by 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 be work in once-through regime with a high average FP-concentration being continuously fed by TRU's together with fission products. Such 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.

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 are 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 an significant potential of HTR type fuel to keep an extremely high burnup.

C.Rübbia proposes to achieve an extraordinary high maximum TRU-burnup ($B_{max}$ ~ 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 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.

There is a simple proportion between the maximum $B_{max}$ and the average $B_{av}$ burnup levels due to an "exponential" type of the fuel concentration evolution law:

$$B_{av} = \frac{B_{\max}}{\ln(1 - B_{\max})} + 1 \qquad (1)$$

which is valid independently upon cross sections or flux levels. It means that if one wants to reach $B_{max} = 0.999$, (as it was indicated in the C.Rubbia's proposal) then the average burnup in a core has to be equal to $B_{av} \approx 0.86$. The correspondent level of fission product concentration will be high enough. It leads inevitably to a subcritical state despite a high TRU concentration ($K_{eff} = 0.8$ - 0.9). Such a system requires supplementary neutrons and can find them in the form of an intensive spallation neutron source.

It has to be mentioned that $K_{eff}$ value is very dependent on the $B_{av}$. At the same time, nuclear waste mass level is proportional to ($1-B_{max}$). One can assess the sensibility of the waste mass ("Waste") to the $B_{av}$ variation as

$$\left|\frac{\delta Waste}{Waste}\right| = \left|\frac{\delta B_{\max}}{1 - B_{\max}}\right| \qquad (2)$$

and if $B_{max} \to 1$ then, taking into account expression (1), one can get:

$$\left|\frac{\delta Waste}{Waste}\right| \approx \left|\ln^2(1 - B_{\max})\right| \delta B_{av} \qquad (3)$$

For the particular case, in the vicinity of Bmax = 0.999, on can evaluate the sensibility of waste mass to burnup as:

$$\left|\frac{\delta Waste}{Waste}\right| \approx 40\delta B_{av}$$

This assessment 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 drawbacks of this concept are:

- economical competitiveness is going to be questionable due to in 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.

### 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). The special code for evaluation of the neutron consumption/production potential of fuels at equilibrium state (see also paragraph 3.4.) has been created [1].

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 $cm^{-2}s^{-1}$ | $\Phi = 10^{15}$ n $cm^{-2}s^{-1}$ | $\Phi = 10^{16}$ n $cm^{-2}s^{-1}$ | $\Phi = 10^{17}$ n $cm^{-2}s^{-1}$ |
|---|---|---|---|---|
| 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 , FRS'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 C.Rubbia.

It is known that Th-based fuel family (for both closed cycle and once-through cycle) consists mostly of uraniums 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 ~ $10^3$ years after fuel irradiation.

The EA inherits the traditional fuel element design (the solid "non-mobile" fuel concept), however, 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, it was decided to use the subcritical regime of work based on the ADS technology 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 of 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 small subcriticality ($K_{eff}$ = 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 principal drawbacks of the EA:

- *Economic competitiveness is questionable: 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-authorised 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.

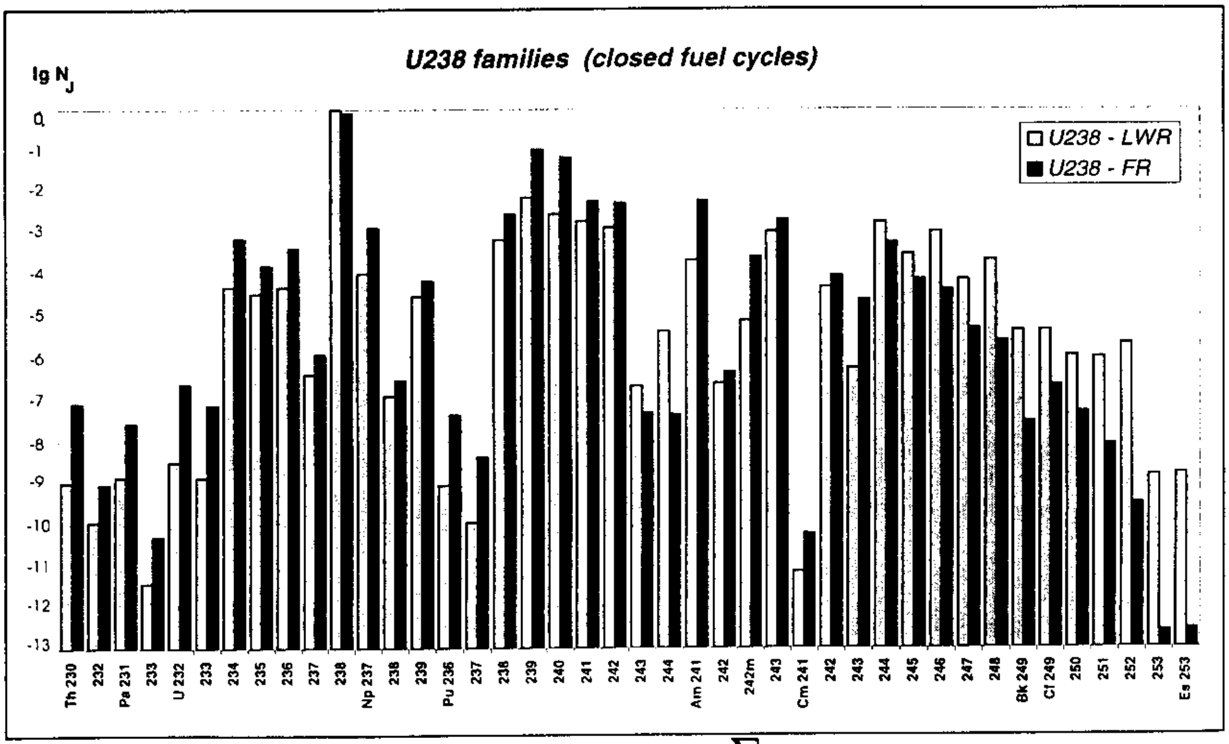

*Figure 1.* $^{238}U$ *family normalised concentrations* $N_J$ ($\sum_J N_J = 1$) *at equilibrium when irradiated in two different spectrum types (Light Water Reactors and Fast Reactors).*

### 3.2. The "TASSE" by CEA [9]

Initially, this concept was born as an attempt to simplify the expensive and worrying fuel recycling, reactor designs, its safety means for the account of the elimination of the reprocessing, the fuel enrichment. 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 is the "**equilibrium**" state of the fuel and FP concentrations.

*An "equilibrium state"* of the fuel isotope concentrations -"equilibrium vector" (see, for example, Fig.2) is forming when the all "repeating" processes of the fuel "management" have a time-continuous behaviour, 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".

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 a reactivity swings. It means, that "mobile" fuel concepts only have a potential to approach to real "equilibrium state" and to **"constant" reactivity during fuel burnup**, which is extremely important for both exploitation and safety.

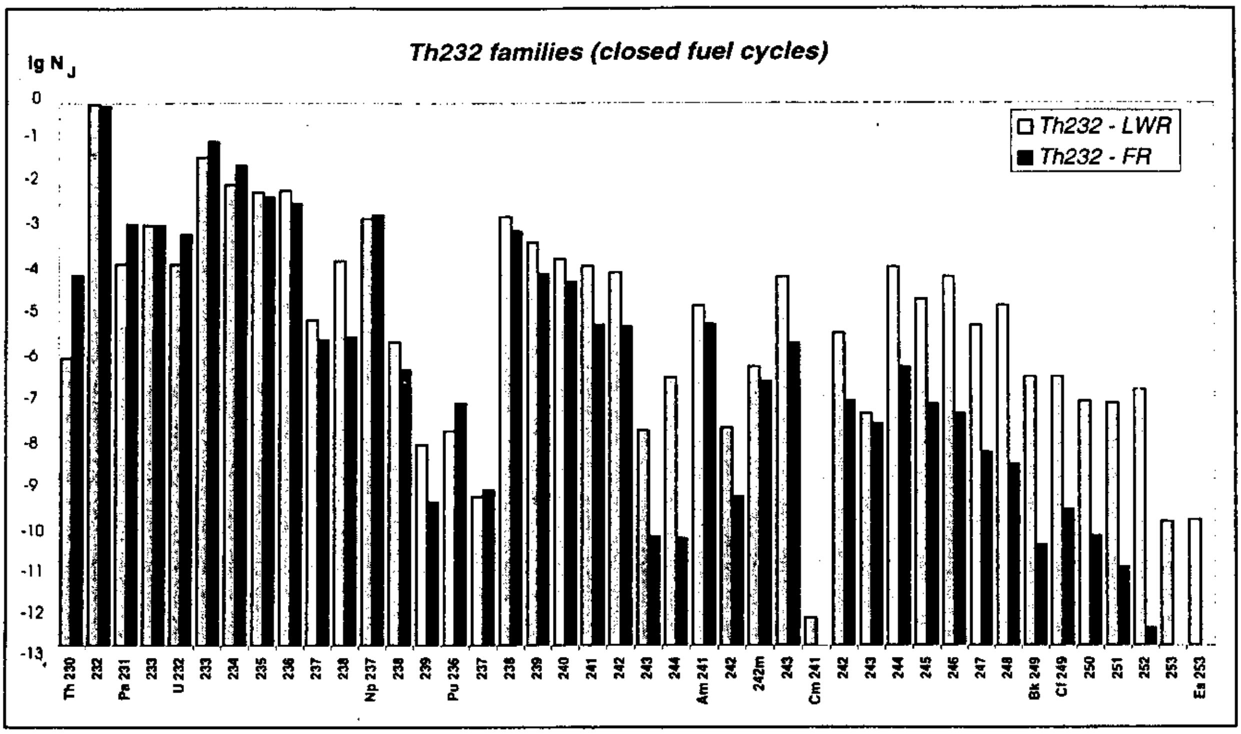

*Figure 2.* $^{232}$*Th family normalised concentrations* $N_J\ (\sum_J N_J = 1)$ *at equilibrium when irradiated in two different spectrum types (Light Water Reactors and Fast Reactors).*

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

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

All initial versions of the TASSE are aiming to use <u>*natural Th*</u> because it has the lowest toxicity after irradiation [10] due to a negligible accumulation of TRU's (Annex 2), enormous natural reserves, attractive (compared with its abundant rival: U-238, see Table 3) neutronics almost for all neutron spectra, attractive non-proliferation potential and low cost.

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 closed cycles, a high burnup is also important because it leads to minimisation of the fuel waste masses.

"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, the 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:

1. For enhancement of the neutron surplus production by a fuel: 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,
2. 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:

1. once-through cycle as the most simple which does not require neither fuel enrichment nor the fuel recycling technology and
2. closed cycle with a simplified reprocessing technology "on line" in the case of strong neutronics constraints to realise once-through cycle.

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) the sufficient potential (the neutron surplus does exceed 0.25n/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 (SPX type) spectrum 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 loosing 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 for fuel 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 treatment) **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.

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.*

In an extreme case, one can use an enriched U fuel, the critical regime and fuel recycling when approaching to AMSTER concept. However, the important part of the fuel cycle simplification will be lost.

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

| Spectrum type | $\Phi = 10^{13}$ n $cm^{-2}s^{-1}$ | $\Phi = 10^{14}$ n $cm^{-2}s^{-1}$ | $\Phi = 10^{15}$ n $cm^{-2}s^{-1}$ | $\Phi = 10^{16}$ n $cm^{-2}s^{-1}$ |
|---|---|---|---|---|
| | -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 |

Remark: A relatively modest neutron consumption of U-233 supplies the natural Th-cycle with a modest but acceptable (regarding ADS) neutronics even in the equilibrium state

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:

1. "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 replacing by TASSEs, no total NP park growth is envisaged.
2. "Long-term stage": equilibrium Th-based cycle with fuel recycling ("On-line" reprocessing technology is probably required for best economics) and again the modest subcriticality (small power accelerators) is sufficient if there is no growth of NP park.
3. If an important temporary/permanently growth of NP power is foreseen, there are several ways to do that:
    * once-through cycle will be applied with a TASSE park doubling time potential of 30-40 years. However, (at least temporary) either powerful accelerators will be required or enriched U fuel reserves can be involved:
    * U-235 enriched fuel reserves can be used without any risk to increase waste toxicity (no waste is foreseen),
    * a combination of these means can be applied.

One of the specific attractive features of the molten salt fuelled TASSE concept is the following:
*Beginning with the transitory stage, no essential radioactive waste is expected to be produced by TASSE, except negligible U and TRU equilibrium wastes if on-line reprocessing of the fuel slightly contaminated by TRUs (long-term stage) is applied.*

There is another radical way for maximising $K_{eff}$ for once-though 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 result, $K_{eff}$ will improving, 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). 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 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 looses 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, loosing fuel cycle simplicity and, probably, decreasing the natural safety potential.

## 4. CONCLUSION

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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# Comparative potential of the future NP

## *Benefits*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| I - Tox | 50 | 10-1000 | 20-1000 | 100 | 100-1000 | 5 | >100 |
| II - Simpl | (?) | + | + | +(?) | - | + (for Burners) | + (for Burners) |
| III - N.Safe | - | + | + | + | - | - | - |
| IV - Fuel R | - | + | + | + | + | - | - |
| V - Prol | - | + | + | - | - | + (for Burners) | + (for Burners) |

Abbreviations:

Tox - the toxicity reduction average factors (a conservative assessment when compared with LWR-open cycle)

Simpl - simplification of reactor/fuel cycle potential

N.Safe - the potential of the natural safety strategy realisation

Fuel R - fuel reserves expansion

Prol - an essential enhancement of the resistance to weapons material proliferation

## *Characteristic Features*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1. Spectr | well-therm | well-therm | fast | fast | fast | well-therm | Resonant |
| 2. Cycle | closed | open/closed | open/closed | closed | closed | open | open |
| 3. Enrich | + | - | - | - | -(?) | - | - |
| 4. Fuel | U5 + (TRU) molten salt | Th | Th | U8- nitride | Th | TRU | TRU |
| 5. Cool | molten-salt | gas, salts | gas, Pb, salts | Pb/Pb-Bi | Pb | molten-salt | gas |
| 6. Regime | critical | ADS | ADS | critical | ADS | ADS | ADS |
| 7. Burnup | ≤10% | 10 - 20% | 20 -40% | 10% | 15% | 70% | > 99% |
| 8. Probl | U-236<br>On-line reprocessing<br>Delayed neutr. deficit | ADS<br>On-line reprocessing if needed | ADS<br>On-line reprocessing if needed | Pb-technol | ADS<br>Pb-technol | ADS | ADS<br>fuel's DPA |

Abbreviations:

Spectr - neutron spectrum type

Cycle - fuel cycle type

Enrich - necessity of the fed fuel enrichment fed fuel type

Fuel - feed fuel (without recycled one)

Cool -coolant

Regime - Regime of work: critical or subcritical

Burnup - the level of fuel burnup in % of heavy atoms

Probl - envisaged technological problems to be solved

**AMSTER**
**EDF**

ADS
**TASSE**
**CEA**

ADS
**TASSE**
**CEA**

**BREST**
**MinATOM**

ADS
**EA**
**CERN**

*EMERGING SYSTEMs*

**LWR's +**

**TIER 1**
(Ch.Bowman)
ADS

**RBR**
(C.Rubbia)
ADS

*SYMBIOTIC SYSTEMs*

## ANNEX 1 . On NEUTRON BALANCE ENHANCEMENT at EQUILIBRIUM

The neutronic potential of any nuclear fuel can be assessed by the analysis of the multiplication factor $K_\infty$ sensibility to every isotope of this chain for the fuel medium at the equilibrium.

If one defines $K_\infty$ roughly as:

$$K_\infty = \frac{\nu \sum_i \sigma_i^f \rho_i}{\sum_i \sigma_i^{c,f} \rho_i} \tag{1}$$

where the fuel-family is producing by the "father" (i = 0) under neutron irradiation and consists of i - isotopes with the concentrations $\rho_i$ and similar $\nu$ values.

At equilibrium, the following relation between two neighbouring isotopes takes place (neglecting decays):

$$\sigma_{i-1}^c \rho_{i-1} = \sigma_i^{c,f} \rho_i$$

Then, one can transform (1) into

$$K_\infty \cong \frac{\nu \left( \frac{1}{\alpha_0} + \sum_{l=1} \frac{1}{1+\alpha_l} \prod_{s=i}^{l-1} \frac{\alpha_s}{1+\alpha_s} \right)}{\frac{1+\alpha_0}{\alpha_0} + \sum_{m>1} \prod_{s=i}^{m-1} \frac{\alpha_s}{1+\alpha_s}} \tag{2}$$

where l - fissionable nuclides, m -all nuclides of the chain, $\alpha_i = \frac{\sigma_i^c}{\sigma_i^f}$

It means that neutronics potential of the chains are defined by combinations of $\alpha$-value of all chain "families".

Fuel cycles (based on the natural fuels: either natural Th or U-238) begin with the nucleus (the father) with the important capture of neutrons, i.e. $\alpha_0$ -values $\rightarrow\infty$. The first "daughter" nucleus (U-233 or Pu-239), on the contrary, has a low $\alpha$ followed by almost non-fissile nuclide (U-234, Pu-240). The analysis of the equilibrium of these chains shows that fuel neutronics is directly sensitive to $\alpha$ -value of all nuclides of the chain but not to their equilibrium concentrations.

For example, if there are m-neutron consumers above the first "daughter" (i = 1) then

$$K_\infty = \frac{\nu}{2(1+\alpha_1)+\alpha_1(m-1)}$$

It means that each next consumer of the chain penalises the multiplication factor in such manner as the first daughter has a "doubled" $\alpha$.

For example, U-236 in the chain of U-235-father "multiplies" the $\alpha$ of U(235 by factor of 2 which leads to significant reduction of the $K_\infty$. Similar situation takes place in Th-based chain regarding U-234, and in U-238 chain regarding Pu-240 for all spectra where U-234 and Pu-240 have relatively low fission cross-sections (or, more correctly, an important $\alpha$-values).

Th-based fuel has U-233 as the first "daughter" (Pa-233 is decaying quickly) with relatively small $\alpha$ in all spectra (with a weak sensitivity of the $\alpha$ and of $\nu$ to spectrum type) following by the "third" fissionable daughter- U-235. Hence, a "negative" role of U-234 in the equilibrium neutron balance is modest (i.e. the TASSE concept). On the contrary, U-235 has a long chain of "non-fissionable" daughters: U-236, U-237, U-238 and each of them is "multiplying" $\alpha$ as well as the total neutron capture. That is why separation of U-236, U-237 is important (i.e. the AMSTER and other concepts based on U-235 utilisation in closed fuel cycle). Neutron consumption of U-238 is compensating by production of "fissionable" Pu and U-238 separation is beneficial only if TRU reduction is required.

For more general cases, the following conclusions is coming from analysis of (2):

1. Every "fissionable" (with a low $\alpha$) daughter (l, l+1,....) in the chain reduces the neutron production of all subsequent daughters due to multiplying this capture contribution by factors of $\alpha_l \times \alpha_{l+1} \times$....
2. Every "fissionable" (with a low $\alpha$) daughter reduces the neutron capture due to appearance a relatively small member $\frac{\alpha_m}{1+\alpha_m}$ among $\prod_s$ in the denominator of (2).
3. To achieve the most positive neutronics potential at equilibrium, is desirable to use the neutron spectrum with a lowest $\alpha$ of majority of chain members by:

- separation of the most $\alpha$-significant nuclides such as U-234 (in Th-cycle), U-236 (in U-235 cycle);
- using neutron spectrum with allows to reduce $\alpha$ for majority of isotopes. At least, "frequent" appearance of fissile nuclide among chain member have to be "designed".

For example, in the standard fast spectrum (SPX), $K_\infty$ value for natural Th-fuel at equilibrium is about 1.13. If one could use a harder spectrum at "point-wise" energy about 1 MeV, then $K_\infty$ is increasing up to $K_\infty$ = 1.20 mostly due to reduction of $\alpha$ -

value of U-234. Further spectrum hardening (say up to energy 2 MeV, if it is possible) would lead to the further growth of $K_\infty$ up to 1.45 because of $\alpha$Th-232 important reduction. The external neutron source of hard neutrons (spallation, fusion,...) can be the reason of similar spectrum transformation.

4. The standard LWR's spectrum has an unfavourable neutronics potential for both Th and U natural fuels when are going to use at equilibrium's ( i.e. for closed fuel cycles). The potential of a thermalised spectrum is better, however, very limited due to small variation of $\alpha$-values. On the contrary, fast spectra are more perspective for neutronics enhancement, however, an important neutron leakage can be a factor of constraints.

**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<br>*<br>**~0** | factor of 3<br>*<br>**~1** | ⇐ feed masse reductions,<br>⇐ fuel cost reduction (*) |
| Fuel recycling, waste management's | **20** | factor of 10<br>fuel discharge repository only<br>**~2** | factor of 3<br>simplification of reprocessing technology<br>**~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 *current* cost is postulated |
| | - | **> 1000**<br>↑↑<br>**~ 20**<br>↑ | **> 1000**<br>↑<br>**>1000**<br>↑ | **Supplementary advantages**:<br>Fuel reserves growth factor<br>Proliferation resistance<br>Fuel waste toxicity reduction factor<br>Natural safety strategy |