THE TASSE CONCEPT (THORIUM BASED ACCELERATOR DRIVEN SYSTEM WITH SIMPLIFIED FUEL CYCLE FOR LONG TERM ENERGY PRODUCTION)

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ABSTRACT

Within the framework of the nuclear waste management studies, the "one-component" concept has to be considered as an attractive option in the long-term perspective. This paper proposes a new system called TASSE ("Thorium based Accelerator driven System with Simplified fuel cycle for long term Energy production"), destined to the current French park renewal. The main idea of the TASSE concept is to simplify both the front and the back end of the fuel cycle, and his major goals are to provide electricity with low waste production, and with an economical competitiveness.

1. INTRODUCTION

The long-term perspective of Nuclear Power is an important subject of discussion nowadays. In France, within the framework of the Bataille law, numerous investigations are conducted to find a range of solutions for the effective management of nuclear waste.

In the present paper, we propose a new concept called TASSE: "Thorium based Accelerator driven System with Simplified fuel cycle for long term Energy production" that has been designed as a part of a long-term strategy for the renewal of the current reactor park.

The TASSE design goals have been chosen in accordance with long term energy requirements such as: to reduce the nuclear waste production, to eliminate the waste already accumulated, to improve the economical competitiveness, to use the natural resources in an optimal way, and to enhance the non-proliferation. These features, as well as the principle of the park renewal, are presented in the first part. In the second part, the equilibrium state of TASSE is presented, with two different mobile fuels: the molten salt fuel and the pebble type fuel. Then we will show some outstanding results such as the reduction of the nuclear waste toxicity. Finally, the results of the transition phase are given, in terms of PWR waste incineration performances.

2. THE TASSE CONCEPT

2.1. *Context*

In France, numerous investigations are conducted within the framework of the nuclear waste incineration management. Two approaches are taken into consideration.

In the first approach, reactors dedicated to waste incineration are part of the nuclear park in two different ways. Either in the concept called "double strata", or in the concept "double component". In the double strata concept, several types of dedicated reactors operate complementary added to the electricity producer one (PWR: Pressurized Water Reactor). In this strategy, a complicated and efficient fuel cycle is required in order to separate and incinerate Pu (Plutonium), MA (Minor Actinides), and LLFP (Long Lived Fission Products), as well as a complicated reactor park containing multiple reactor types. Nevertheless the radiotoxicity reduction is significant (about a factor 100), and the use of the ADS system (for the MA and LLFP transmutation) allows one to reduce the number of necessary dedicated reactors. In the double component concept, only one type of dedicated reactor is added to the PWR park. This reactor manages all the wastes from the PWRs (Pu, MA and a part of LLFP). This strategy allows a less efficient fuel cycle [1], [2].

The second approach consists of replacing the PWR reactor itself by an innovative system, which is able to produce electricity, with a very low TRU (Transuranium) production. This radical long-term strategy involving the renewal of the reactor park is called the "one component" approach.

The TASSE concept, which is presented in this paper, takes part in these studies [3] [4].

2.2. *TASSE characteristics*

The main characteristics of TASSE fulfill specific requirements such as:

- ✓ a long term economically competitive nuclear energy production,
- ✓ a very low long-lived radiotoxic waste production,
- ✓ the elimination of waste already accumulated by the current reactor park,
- ✓ an enhanced safety and non proliferation features.

The main idea of the TASSE concept is to simplify both the front and the back end of the fuel cycle (e.g. neither fuel enrichment nor fuel reprocessing are foreseen, or just the fission products separation). This aspect can improve the economic competitiveness as well as the public acceptance.

With the purpose of a radical reduction of the waste toxicity level (at least up to 10,000 years after storage), the thorium cycle has been chosen for TASSE. Indeed, the Thorium cycle has the advantage of a low production of actinides, which are the major contributors to the PWR waste toxicity. Moreover, the Thorium cycle has got important natural resources, which could allow a longer utilization of Nuclear Energy [5].

Operating with high burn up is crucial for economical and environmental aspects. To reach a high burn up level, two types of fuel have been considered: molten salt and pebble-bed fuel. Both fuels are called "mobile", because they circulate through the reactor, which leads to an equilibrium nuclide composition in the core [6]. In addition to this aspect, since the mobile fuel stay longer in the core, one can reach higher burn up and extract more energy from the fuel. This characteristic is crucial from the economical point of view.

The fast neutron spectrum is chosen because of its potentially better neutron economy. This can be observed in the Table 1, which represent the overall neutron production [6], [7] for the ^{232}Th in two different spectra and flux level.

Spectrum / flux (n/cm^{2}s)	10^{14}	10^{15}
Fast (SPX)	0.36	0.36
Thermal (PWR)	0.17	0.01

Table 1: Overall neutron production / fission of ^{232}Th

Finally, TASSE is operating in sub-critical mode. The reason of the sub-criticality is rather particular. Since the use of the non-enriched thorium cycle is associated to a tight neutron economy, the use of an external source is mandatory. So, in this concept, the utilization of the sub-critical mode is original, as it is associated with a strategically choice instead of, for example, safety enhancement reasons.

2.3. *Park renewal*

Figure 1 shows the conceptual scheme for transition from the present reactor park to TASSE system, where the TRU from PWRs are used to start new TASSE systems. In this case, two goals can be reached: increase of the low reactivity of TASSE at the starting (due to the non-enriched fertile thorium fuel), and the transmutation of the "waste" already accumulated by the present reactor park.

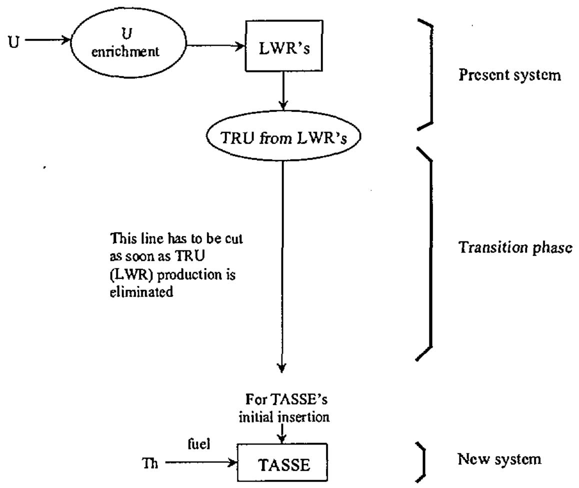

Figure 1: From LWRs and U-cycle to TASSE with natural Th feed

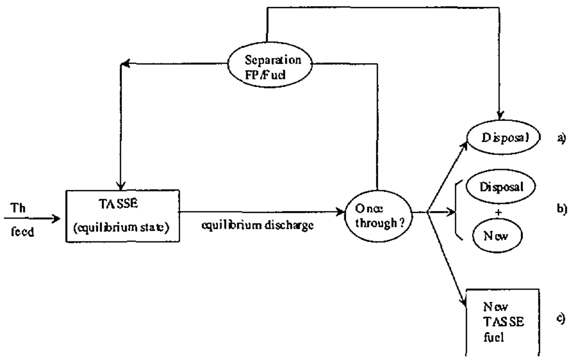

Figure 2: Fuel cycle options for TASSE at equilibrium state

Two fuel cycle have been considered for the TASSE concept: a once-through (no reprocessing of the irradiated fuel) version and a so-called "closed-cycle" version (on-line separation of the fission product). In both cases, no fuel enrichment is foreseen (see Figure 2). In the once-through version, three further option are considered namely:

- ✓ No expansion of the nuclear park. The irradiated fuel is sent to storage for disposal (option a)
- ✓ Expansion of the nuclear park. The irradiated fuel is sent directly to a new TASSE as an initial inventory (option c)
- ✓ An intermediate situation can be envisaged sharing the irradiated fuel between disposal and new TASSEs or using a partial reprocessing (option b).

3. COMPUTER CODES AND PROCEDURES

For the following calculations, the French reactor physics code system ERANOS developed at CEA has been used [8], coupled, for ADS calculations, to the HETC [9] code in order to assess the spallation neutron source.

For the equilibrium calculations, only the multi-cell code ECCO is used. The formalism used to solve the multi-group Boltzmann transport equation is the collision probability method. The fast spectrum standard 33-group cross section library is issued from JEF2.2 [10].

4. MOLTEN SALT FUEL

For historical and chemical reason [11], the studied molten salts are essentially fluorides ones. The main characteristics of the different molten salts studied for TASSE (in order to find an optimal one) are gathered in the table 2 [12].

composition (molar %)	ThF_4 30% NaF 24.5% PbF_2 45.5%	ThF_4 32% NaF 13.5% LiF 54.5%	ThF_4 12% BeF_2 16% LiF 72%	ThF_4 22% NaF 11% KF 67%
density (g/cm^3)	7	3.31	3.35	2.64
Melting point (°C)	600	525	500	535

Table 2: TASSE molten salts characteristics

The equilibrium condition is defined by two important parameters: the neutron spectrum and the choice of the burn up level. In this case, one can find the optimum neutron multiplication for the set of equilibrium states.

4.1. *Spectrum*

The neutron spectra in TASSE with molten salt fuel are fast, but with a significant epithermal component. This can be noted in Figure 3, which represents the spectrum of TASSE for one molten salt (TASSEs for all the different molten salts have got the same spectrum) compared to the SPX spectrum (reference for the fast spectrum).

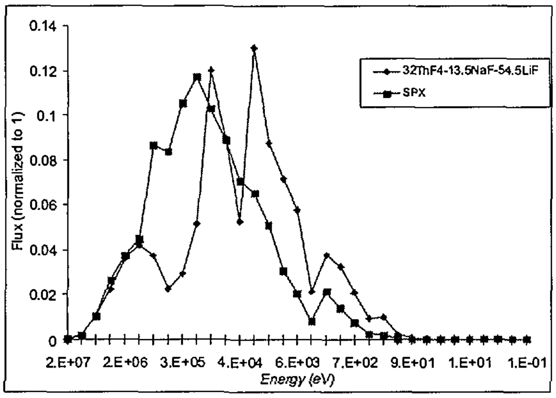

Figure 3: TASSE molten salt and SPX spectrum (normalized to 1)

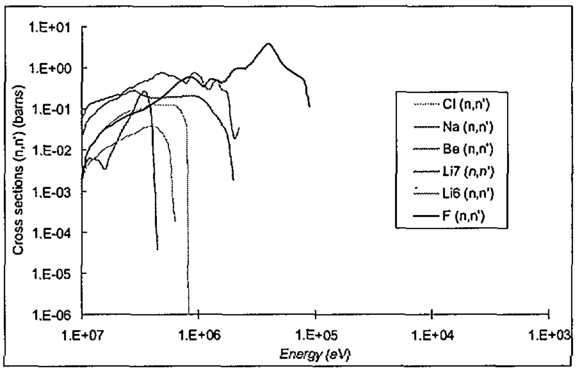

Figure 4: Inelastic cross section of various light isotopes presents in TASSE molten salt

This shift towards the epithermal energy range is due to the fluorine. This element is present in important quantities in all salts and presents a significant inelastic cross section (4 b) in the fast energy range (see Figure 4).

4.2. *The burn up choice*

For molten salt fuel, the burn up (BU) is defined as the percentage of FP (Fission Products) present in the salt. Because of the "on-line" charge and discharge of the fuel, there is a different equilibrium state for each burn up level.

An essential feature of the TASSE concept is the choice of the appropriate burn up. The main idea is to choose the burn up, for the once-through cycle, corresponding to an "optimal" value of the reactivity, which is approximately kept constant all over the cycle.

In Figure 5 presents the relation between the k_∞ and the burn up (% h.a.) level both for the case of the once-through cycle and for the "closed" cycle.

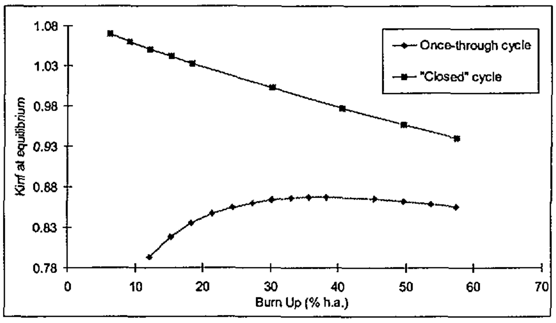

Figure 5: Reactivity at equilibrium in function of the burn up level

As the discharge rate is inversely proportional to the burn up, when the BU is too low, the discharge rate is high, that makes it difficult to accumulate ^{233}U (in the once-through cycle). Then, one can observe that the reactivity level at equilibrium is increasing with the burn up. But, with high BU, the discharge rate is low, and the core becomes poisoned by the FP. The neutronic balance at equilibrium is once again unfavorable. Hence, the reactivity at equilibrium has got an optimal value corresponding to a certain burn up level. In "closed" cycle, all the heavy nuclides return to the core after FP separation. So, the highest reactivity level is reached for the lowest BU. Hence, the choice of the burn up level is a compromise between the reactivity level, and the discharge rate.

Among the four studied molten salts, the best neutronic results are obtained with $32ThF_4$-13.5NaF-54.5LiF and $30ThF_4$-24.5NaF-$45.5PbF_2$. One obtains the infinite multiplication coefficient k_∞ in the vicinity of 0.9 for the once-through cycle with a maximum burn up of 38% (% h.a.), and a k_∞ of 1.05 for the "closed" cycle with a burn up of 12%.

4.3. *Remarks on the results*

The low reactivity level obtained in the once-through cycle is due to the non-enrichment of the fuel and the loss of fissile material during the discharge.

In order to improve the neutronic balance in the once-through cycle, a chloride salt has been investigated. Because of the fluoride, the TASSE fast spectrum was deteriorated. Since the fast spectrum gives better neutronic results, the chlorides became an interesting alternative. But, as natural chloride salt fuel suffers from intensive neutron capture, no improvement can be reached in term of reactivity level.

With respect to molten salt fuel in the once-through cycle, two possibilities of improvement can be foreseen: either the isotopic separation of Cl (in order to eliminate the absorber ^{35}Cl, which gives ^{36}Cl, which is radioactive with an half life of 300,000 years), or the use of fluoride salts with a higher actinide concentration (in order to have harder spectrum).

5. PEBBLE-BED FUEL

With the intention of improving the results in the once-through cycle, another type of fuel has been investigated: the pebble-bed fuel. The fuel considered here is similar to the HTRs' pebble-bed fuel with replacement of graphite by steel matrix (this choice is made for exploratory studies, but can improve) to keep a fast spectrum. One can notice, in Figure 6, that the TASSE Pebble-bed spectrum is as hard as the SPX's one.

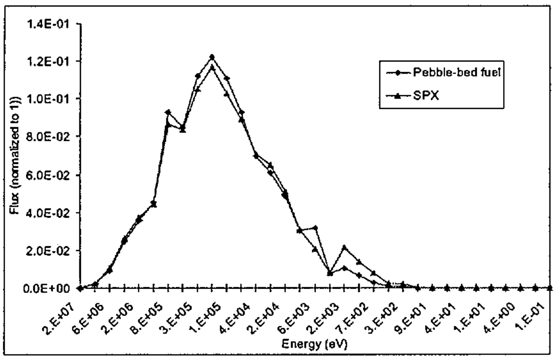

Figure 6: TASSE pebble-bed and SPX spectrum (normalized to 1)

Thus, with such a fuel, the optimal value of the reactivity at equilibrium, in once-through cycle, is higher compared to the molten salt fuel. The k_∞ value is 0.95 for an average burn up of 17% (h.a.).

6. OUTSTANDING RESULTS

Figure 7 shows the mass proportion of the most important heavy nuclides. Two cases are taken into account: TASSE molten salt (with $32ThF_4$-13.5NaF-54.5LiF) in "closed" cycle, and TASSE pebble-bed in once-through cycle. The major isotopes are, as expected, the ^{232}Th (around 80-90%), and the ^{233}U (8-9%). One can notice the very low production of TRU (less than 1%).

The low quantity of TRU in the fuel at equilibrium has an important impact on the waste toxicity. For the TASSE concept, in both cycles, a significant gain in term of toxicity is obtained (in comparison with PWR discharge). In once-through cycle, a factor 20 to 1000 (depending on the time scale) is foreseen, and the toxicity reduction, in "closed" cycle is expected to be 10^4 (see Figure 8).

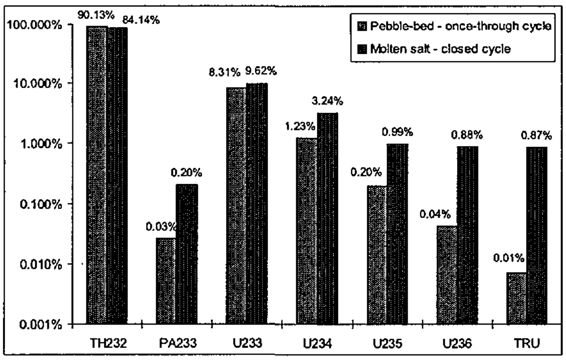

Figure 7: Masses proportion for major heavy nuclides at equilibrium

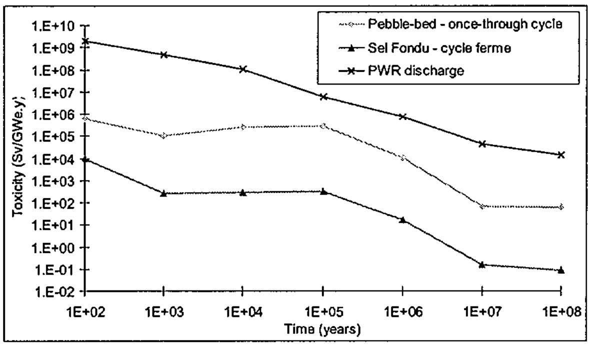

Figure 8: Toxicity versus time for TASSE and PWR discharge

Finally, one has to be reminded that operating at a sub-critical level is mandatory. The strategic choice of the fuel cycle simplification leads to an original utilization of the ADS concept. In this respect, we can consider the use of the accelerator as a way to eliminate a complicated fuel cycle.

7. CORE LAYOUT

Some core layouts have been preliminary studied for TASSE using the optimal fuel composition at equilibrium. The reactor is designed for an electricity production of 1GWe.

Regarding the "closed" cycle, the molten salt fuel is the best option, and two types of core layout can be considered. In the first one, the core volume is around 70 m^3, with 90 tons of fuel inventory (with $32ThF_4$-13.5NaF-54.5LiF salt). The proton beam (1GeV) interacts with a Pb-Bi spallation target (spallation efficiency: 27 n/p). This configuration leads to a reactivity of 0.97 at equilibrium, and a proton current requirement of 33 mA. The energy fraction required to be returned to the accelerator is 7.5%.For the second envisaged layout, the $30ThF_4$-24.5NaF-$45.5PbF_2$ salt is used as fuel (100 tons) and as a spallation target. The spallation efficiency is lower than that reached for a Pb-Bi target (20 neutrons/proton), but this concept allows important design simplifications (no target making, and, due to molten salts, no irradiated fuel transports). This configuration requires a proton current of 6 mA and achieves a reactivity level of 0.99. The energy fraction returned to the accelerator is only 1%. Both options in "closed" cycle require a reasonable proton current.

In open cycle, the pebble-bed fuel seems to be preferred. Here again, the proton beam (1GeV) interacts with the spallation target made of Pb-Bi. Due to the low specific power (characteristic of the pebble-bed fuel), and in order to reach the same power level (1GWe), the core dimensioning leads to a volume of 250 m^3, i.e. containing 530 tons of fuel. The neutron leakage is reduced due to the large core size. In addition to this characteristic, the good spallation efficiency allows one to reach a reactivity level of 0.91 in the once-through cycle. The proton current required is 85 mA, and the energy fraction returned to the accelerator is 22%. Nevertheless, this option needs technical improvements (important core size and proton current required).

8. TRANSITION PHASE

The transition phase corresponds to the period in which the PWR park is replaced by the TASSE park. The first TASSE reactor is started with natural Thorium plus TRU from PWR discharge. This helps to increase the initial reactivity level (which is too low with only non-enriched fertile thorium), and to incinerate the PWR waste. But one has to remind that natural Th only composes the feed. This study has been made only with the $32ThF_4$-13.5NaF-54.5LiF salt in once-through cycle.

The maximal quantity of TRU in the initial inventory is given by the chemistry. Indeed, for solubility reasons, the value of 6% (molar) of $TRUF_4$ in the fuel is considered as a limit. This leads to an initial reactivity of 0.90, which is kept constant during the path to the equilibrium. For the core layout previously described, this quantity corresponds to an insertion of 10 tons of TRU in the fuel. At equilibrium, only 0.4 tons of TRU are present.

In Figure 9, the time-evolution of the major isotopes concentration are shown. One can see the evolution towards equilibrium for the ^{233}U and ^{234}U, and the decrease of the TRU concentration. Finally, 95% of the TRU are burned in approximately 45 years. This last characteristic is also important regarding the necessity to reduce the TRU stock in a time period as short as possible.

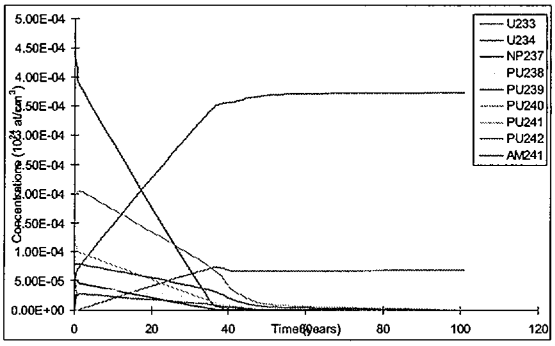

Figure 9: Time-evolution of the major isotope concentration

9. CONCLUSION

This paper presents new developments on a new reactor concept called TASSE ("Thorium based Accelerator driven System with Simplified fuel cycle for long term Energy production"). TASSE is an electricity producer, and, in a long term perspective, could be an option for the renewal of the current French park. TASSE is capable, in an extreme case, of operating without neither fuel enrichment nor fuel reprocessing. In a more realistic option, only the fission product separation is foreseen.

An important result has to be pointed out: the strategic choice of the fuel cycle simplification leads to an original utilization of the ADS concept. In this respect, we can consider the use of the accelerator as a way to simplify the fuel cycle.

In terms of performances, TASSE has shown its burner capabilities. During the transition phase towards a renewal of the power park, TASSE is able to incinerate transuranium elements already accumulated by the current PWR park. In one 1GWe TASSE, about 10 tons of TRU are introduced, in addition to natural thorium, that can be incinerated within about 50 years. This is also important regarding the necessity to reduce TRU stock in a time period as short as possible.

Due to the low production of transuranium elements, the waste toxicity is drastically reduced. TASSE, with the once-through cycle, gives a gain of 20 to 1000 (depending on the time scale) in comparison with PWR discharged fuel in a reprocessing scenario. For the "closed" cycle, the toxicity reduction factor is expected to be 10^4.

Finally, TASSE could have non-proliferation features since its fuel cycle is free of fuel enrichment processes, while reprocessing (if any) does not imply isotopic or element separation.

10. References

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