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Optimized Transition from the Reactors of Second and Third Generations to the Thorium Molten Salt Reactor

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Abstract – *Molten salt reactors, in the configuration presented here and called Thorium Molten Salt Reactor (TMSR), are particularly well suited to fulfil the criteria chosen by the Generation IV forum, and may be operated in simplified and safe conditions in the $Th/^{233}U$ fuel cycle with fluoride salts. Amongst all MSR configurations in the thorium cycle, many studies have highlighted the configurations with no moderator in the core as simple and very promising. Since ^{233}U does not exist on earth and is not being produced today, we aim at designing a critical MSR able to burn the Plutonium and the Minor Actinides produced in the current operating reactors, and consequently to convert this Plutonium into ^{233}U. This leads to closing the current fuel cycle thanks to TMSRs started with transuranic elements on a Thorium base, i.e. started in the Th/Pu fuel cycle, similarly to fast neutron reactors operated in the U/Pu fuel cycle. We will detail optimizations of this transition between the reactors of second and third generations to the Thorium cycle. Such a transition is based on a fleet of TMSRs with no moderator in the core, including TMSRs started with Plutonium and TMSRs directly started with ^{233}U. We developed parametric studies to optimize these TMSRs, amongst which the study presented here, based on one of the main TMSR parameters: the percentage of heavy nuclei in the fuel salt of the TMSR configuration, which modifies the moderation ratio of the reactor and thus influences both the initial fissile inventory and the spectrum of the reactor. We analyze the characteristics of each reactor configuration, in terms of deterministic safety parameters, fissile matter inventory, salt reprocessing, radiotoxicity and waste production, and finally deployment capacities.*

I. INTRODUCTION

Molten Salt Reactors (MSRs), one of the systems selected by the Generation IV forum, may be operated in simplified and safe conditions in the Th/^{233}U fuel cycle and with fluoride salts, whether in a thermal or a fast neutron spectrum[1,2,3,4]. These MSRs are called Thorium Molten Salt Reactors (TMSRs). More precisely, we consider in this study TMSRs with no moderator in the core, the moderation ratio depending only on the salt composition. It has been demonstrated[5] that such reactors can operate with the relevant properties, in terms of breeding ratio, feedback coefficients, production of transuranic nuclei and material steadiness to irradiation.

In Section II, we introduce the TMSR concept with no moderator in the core, also the called non-moderated TMSR. We state the main criteria used to optimize these reactors, such as safety level, radiotoxicity and waste production, and deployment capacities. Regarding these criteria, we present some parametric studies of this TMSR concept: TMSR configurations are evaluated in section III

by varying the reprocessing constraints and the proportion of heavy nuclei contained in the fuel salt.

One of the pending questions concerning TMSRs is the supply of the fissile matter, and as a consequence the deployment possibilities of a fleet of TMSRs, since ^{233}U does not exist on earth and is not yet produced in the current operating reactors. In order to optimize the transition between second and third generation reactors and TMSRs, we choose to produce ^{233}U directly in non-moderated TMSRs started with Plutonium as fissile matter on a Thorium basis, and then operated in the Th/^{233}U cycle[5]. We aimed at designing a reactor able to burn the Plutonium and the minor actinides produced in currently operating reactors to close their fuel cycle, and consequently to convert this Plutonium into ^{233}U. Such Pu-started TMSRs are studied and evaluated in section IV.

Finally, the full transition between the second and third generation reactors to the Thorium cycle is optimized in the second and third sections by considering the deployment capacities of each TMSR considered, both Pu-started and ^{233}U-started configurations. The main constraint of a sustainable power deployment is the saving

of resources, i.e. in our case the best conversion of Plutonium in [233]U and the configurations allowing the shortest doubling times, as detailed in section V.

This work is based on the coupling of a neutron transport code called MCNP[6] with the materials evolution code REM[3,7]. The former calculates the neutron flux and the reaction rates in all the cells while the latter solves the Bateman equations for the evolution of the materials composition within the cells. These calculations take into account the input parameters (power released, criticality level, chemistry ...), by adjusting the neutron flux or the materials composition of the core on a regular basis. Our calculations rest on a precise description of the geometry and consider several hundreds of nuclei with their interactions and radioactive decay; they allow a thorough interpretation of the results.

II. GENERAL DESCRIPTION OF THE REACTORS, PARAMETERS AND CRITERIA

II.A. Description of the non-moderated MSR concept

The general concept of the Thorium Molten Salt Reactor (TMSR) is a 2500 MWth (1 GWe) reactor operated in the [232]Th/[233]U fuel cycle. In this article, TMSRs may be started directly with [233]U or with Plutonium and minor actinides, mixed with Thorium. The reactor is composed of a single large fuel salt channel, 1.25m radius and 2.60m height, as shown on Fig. 1. One third of the 20 m^3 of fuel salt circulates in external circuits and, as a consequence, outside of the neutron flux (Fig. 2).
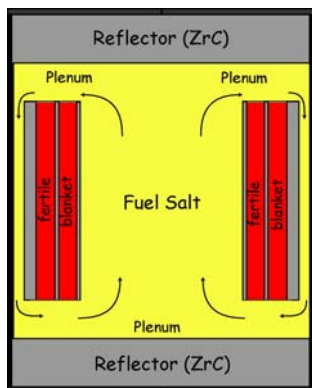

Fig.1. Vertical section of the non-moderated TMSR simulated core

A fertile radial blanket surrounds the core. It contains a binary fluoride salt LiF - ThF$_4$, with 28 mole % of [232]Th. This blanket has been designed such that it stops approximately 80 % of the neutrons, thus protecting external structures from irradiation while improving the system's breeding. The salt channel is also surrounded by

two axial reflectors. These reflectors are made of ZrC in order to avoid the use of a moderator material.
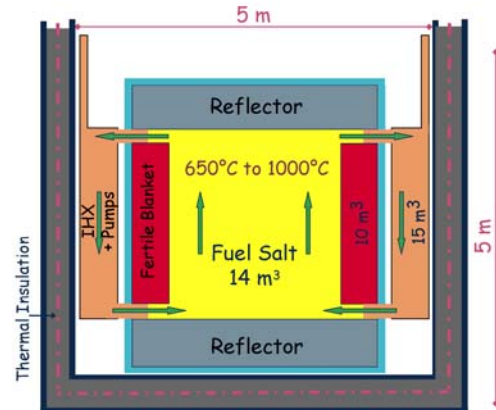

Fig.2. Vertical schematic section of the whole TMSR, including pumps and heat exchangers

We assume that helium bubbling in the salt circuit is able to extract the gaseous Fission Products (FP) and the noble metals within 30 seconds[1,3]. We also consider an off-line reprocessing of the total salt volume in a separate chemical unit, with a complete extraction of the FPs. In this reprocessing, the TRUs are not extracted but are reinserted in the core to insure their self-burning in the TMSR. This off-line reprocessing will be discussed in paragraph III.A. We also assume that the [233]U produced in the blanket is extracted within a 6 month period.

II.B. Reactor parameters considered: Proportion of heavy nuclei in the fuel salt and Reprocessing

In this section, we aim at optimizing this TMSR concept by varying two reactor parameters:
- the composition of the fuel salt, more precisely the proportion of heavy nuclei in the fuel salt;
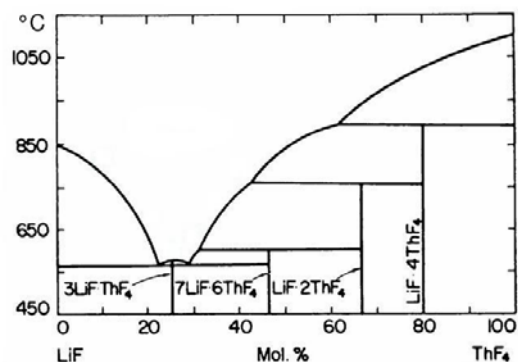- the reprocessing, which modifies the salt composition while modifying the reactor's poisoning by FPs.

Fig.3. LiF - ThF$_4$ phase diagram

The modification of the fuel salt consists in varying the proportion of heavy nuclei in the fuel salt; this has an influence both on the initial fissile inventory and on the spectrum of the reactor. For HN proportions ranging from 20 mole % to 30 mole %, the salt used is a binary fluoride salt LiF-(HN)F$_4$, whose melting temperature is around 570°C (Fig. 3). We thus choose an operating temperature of 630°C, with a corresponding ^{233}U proportion in heavy nuclei of about 3 %, a thermodynamic efficiency of 40 %, and a salt density around 4.3 with a dilatation coefficient[8] of 10^{-3}/°C. For lower proportions of HN, this binary salt is no longer liquid at the operating temperature of 630°C previously selected. Two alternatives can be considered:

- Introducing Beryllium in the fuel salt to lower its eutectic point. The salt is then LiF-BeF$_2$-(HN)F$_4$ at the same operating temperature as before.
- Operating at a higher temperature (around 1000°C), still using a binary fluoride salt LiF-(HN)F$_4$.

The first solution, Beryllium addition, has been chosen in this study to avoid some problems du to much higher operating temperatures, in particular with materials. This choice, in turn, raises new issues such as Plutonium solubility, which we discuss in Paragraph IV.D.

Regarding the second parameter, the off-line reprocessing, the amount of FPs produced in the reactor, and thus to be extracted by the reprocessing, depends only on the power produced. It may be difficult, even impossible, to extract the main FPs (lanthanides) in the presence of HN. As a consequence, and in order to have equivalent reprocessing in every reactor configuration, it is necessary to have the same amount of HN reprocessed per day whatever the HN proportion in the fuel salt. We will first study the influence of this parameter in paragraph III.A. Then, for all TMSRs considered in this article we fix a delayed reprocessing of a salt volume containing 200 kg of HN per day. This choice is detailed in paragraph III.A.

II.C. Criteria used for the TMSR evaluation

Our TMSR optimization is based on three main criteria detailed in this paragraph: the safety level, the radiotoxicity and waste production, and the deployment capacities.

II. C. 1. Safety level
The feedback coefficient is traditionally broken down into three sub-coefficients related to the different components of the core presented above:

$$\left.\frac{dk}{dT}\right)_{total} = \left.\frac{dk}{dT}\right)_{salt\_heating} + \left.\frac{dk}{dT}\right)_{salt\_dilatation} + \left.\frac{dk}{dT}\right)_{graphite\_heating}$$

The third sub-coefficient is negligible in our case since there is no graphite moderator in core.

The uncertainties indicated in this article are a quadratic combination of the statistical and systematic uncertainties on the determination of the sub-coefficients. The statistical errors are precisely estimated by simulation, the quantification of the systematic errors is more difficult. More precisely, concerning the systematic uncertainties on the contribution of salt heating, the cross-sections concerned are well known, inducing only negligible uncertainties. The uncertainties on the salt density and its dilation lead to systematic errors lower than 20% on the contribution of salt dilatation, a value used for the estimation of uncertainties in the next sections.

II. C. 2. Waste production and radiotoxicity
Wastes result both from leakages occurring during the reprocessing and from the final transuranic elements inventories. These transuranic elements inventories present at the end of a reactor's lifespan may be re-injected in a new reactor and are usually not considered as waste, as long as such reactors are operating. But these actinides inventories have to be taken into account for a sustainable waste management, where the entire life of a fleet of reactors, from launching to shutdown, has to be considered. Leakages are proportional to the integral of the transuranic elements inventories and to the amount of HN reprocessed per day (equivalent for all our TMSRs). Leakages occurring all along a reactor's lifespan are negligible compared to the final inventories. Only these final inventories of transuranic elements are thus given for each TMSR, at equilibrium. For Pu-started TMSRs, more precisely here for TMSRs started with the transuranic elements produced in current operating reactors and then operated in the thorium cycle, we estimate the reduction of radiotoxicity reached thanks to these TMSRs at equilibrium, one of our goals being to close the current fuel cycle.

II. C. 3. Deployment capacities
This has to be evaluated both for each reactor configuration and for a combination of Pu-started TMSRs producing ^{233}U and of ^{233}U-started TMSRs, as presented in section V. We first compare the ^{233}U production in a TMSR configuration with its own initial fissile (^{233}U), by considering the reactor doubling time. Then we compare the ^{233}U production by a Pu-started TMSR configuration with the initial ^{233}U inventory necessary to launch the corresponding ^{233}U-started TMSR.

III. THORIUM MOLTEN SALT REACTORS STARTED WITH ^{233}U

III.A. Study as a function of the off-line reprocessing

For each proportion of heavy nuclei in the salt, ranging from 6 mole % to 27.5 mole %, we evaluate by simulation the breeding ratio of each reactor configuration as a function of the amount of heavy nuclei reprocessed per day. The result of this study is displayed on Fig. 4, allowing the visualization of many parameters of interest of the non-moderated TMSR: reprocessing design, reactor deployment and breeding capacities.
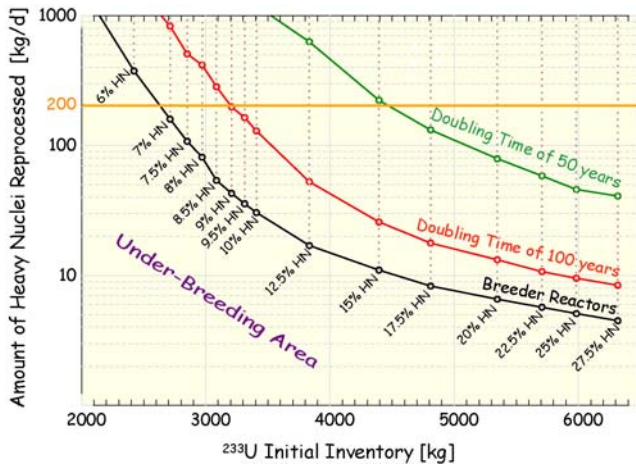

Fig.4. Amount of heavy nuclei reprocessed per day versus initial fissile (^{233}U) inventory, for different heavy nuclei proportions in the fuel

In Fig. 4, the dark line represents breeder reactors, the red one the reactors producing their initial ^{233}U inventory in 100 years (i.e. what is called a doubling time of the reactor of 100 years), and finally the green line stands for reactors producing their initial ^{233}U inventory in 50 years (or a reactor doubling time of 50 years). Under-breeder reactor configurations, which are located under the black line (bottom of the figure), will not be considered in the following since they do not allow any sustainable reactor deployment.

The ^{233}U initial inventory ranges from 2400 kg for a HN proportion in the salt of 6 mole % to 6300 kg for a HN proportion of 27.5 mole %. This corresponds to a variation of the neutron spectrum from an epithermal to a fast spectrum, as shown on Fig. 5.

We chose a reasonable reprocessing rate of 200 kg of HN per day, indicated by the orange horizontal line on Fig. 4. This choice disqualifies TMSRs with HN proportions lower than 7%, since they cannot then be breeder reactors (see Fig. 4).
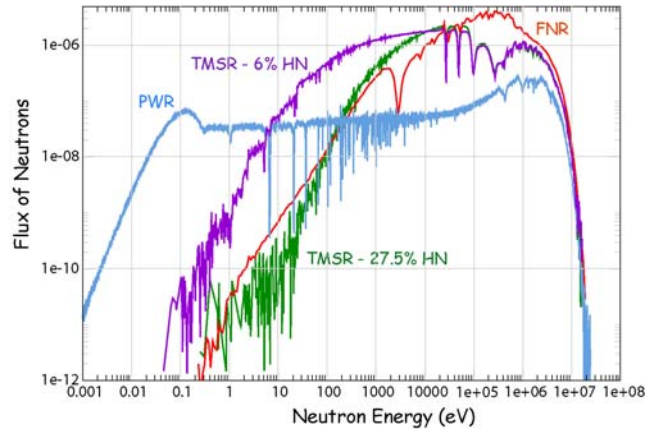

Fig.5. Neutron spectrum of two TMSR configurations (6% and 27.5% of heavy nuclei in the salt) compared to the neutron spectrum in a pressurized water reactor (PWR) and in a fast neutron reactor (FNR)

III.B. Safety level

The total feedback coefficient at equilibrium is displayed on Fig. 6, together with its components, the contributions of the salt heating and salt dilatation, as a function of the HN proportion in the salt. All these safety coefficients are significantly negative for all HN proportions, including the density coefficient which can be viewed as a void coefficient. The total feedback coefficient ranging from -10 pcm/K to -5 pcm/K and thus insuring a very good level of deterministic safety[9] in all these ^{233}U-started TMSR configurations, safety is not a discriminating factor in our case to choose the optimal salt composition.
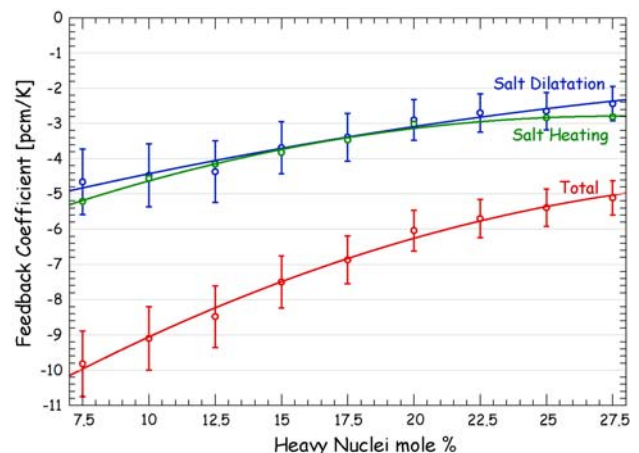

Fig.6. Feedback Coefficients of ^{233}U-started TMSRs at equilibrium as a function of the HN proportion

III.C. Production of transuranic elements

TMSRs are supposed to be at equilibrium after 200 years of operation. The inventories of transuranic elements

obtained are displayed on Fig. 7, for different HN proportions.

The Pu inventory equal to around 300 kg and the Am inventory equal to 7 kg only slightly depend upon the HN proportion. The Np inventory ranges from 100 to 200 kg, and the Pa inventory from 70 to 100 kg. Note that the Cm inventory displayed on Fig. 7, equal to some kilograms, is not correctly evaluated for the higher HN proportions since this inventory does not yet reach equilibrium in these cases. The global behavior of this Cm inventory, however, is coherent with the results presented on Fig. 7.
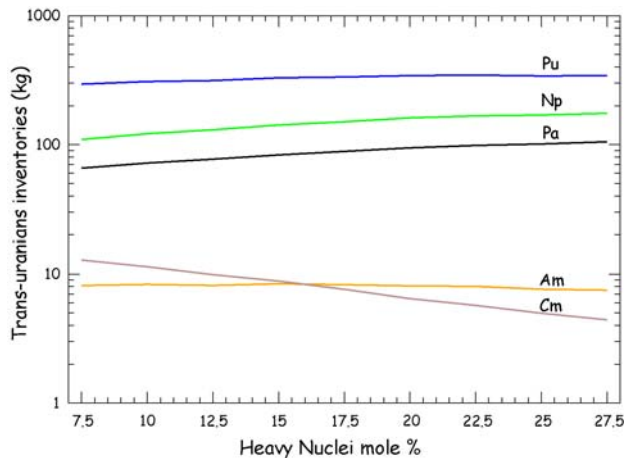

Fig.7. Inventory of the transuranic elements of the ^{233}U-started TMSRs at equilibrium, as a function of the proportion of heavy nuclei in the salt

One tends traditionally to consider that the faster the neutron spectrum is (here the larger the HN proportion is), the lower the amounts of TRU are in a reactor at equilibrium, since the TRU burning is better. We do not observe such a behavior on Fig. 7 because the heavy nuclei inventories are significantly larger for large HN proportions.

Finally the TRU inventories do not really depend upon the HN proportion in the fuel salt, so that this parameter is not discriminating either.

IV. THORIUM MOLTEN SALT REACTORS STARTED WITH PLUTONIUM

The idea in this section is to design a TMSR able to burn Pu while producing ^{233}U, without loosing the advantages of the ^{232}Th/^{233}U fuel cycle. We have thus simulated TMSRs started with Plutonium and Thorium, and then operated in the ^{232}Th/^{233}U fuel cycle, i.e. fed with Thorium. More precisely, to be more realistic, these TMSRs are started with the mix of Pu, Np, Am and Cm listed in Table I corresponding to the transuranic elements of an UOX fuel after one use in a standard PWR and five years of storage[ref].

TABLE 1

Proportions of transuranic nuclei in UOX fuel after one use in PWR without multi-recycling (burnup of 60 GWd/ton) and after five years of storage[10]

Element	Proportion in the mix
Np 237	6.3 %
Pu 238	2.7 %
Pu 239	45.9 %
Pu 240	21.5 %
Pu 241	10.7 %
Pu 242	6.7 %
Am 241	3.4 %
Am 243	1.9 %
Cm 244	0.8 %
Cm 245	0.1 %

Note that these reactors and their fuel salt are completely equivalent to the TMSRs presented in the previous section, except for the initial fuel load.

IV.A. Safety level

The feedback coefficients for Pu-started TMSRs have been evaluated after one year of operation and at equilibrium.
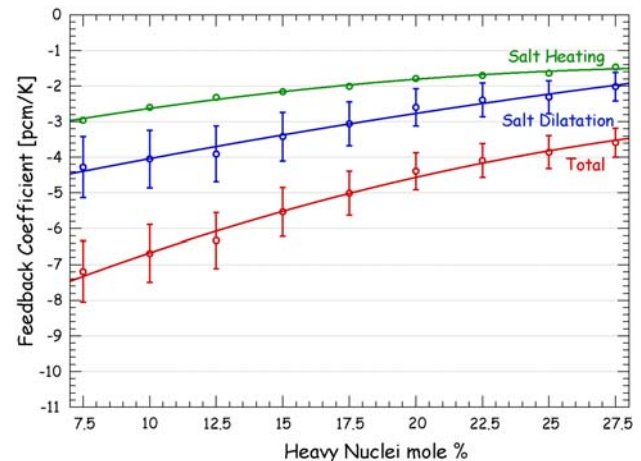

Fig.8. Feedback Coefficients of Pu-started TMSRs after one year of operation as a function of the HN proportion

The total feedback coefficients after one year of operation are displayed on Fig. 11 as a function of the HN proportion, together with their components, the contributions of salt heating and salt dilatation. They correspond to the initial safety behavior of the reactor, since the inventories after one year of operation are quite

identical to the initial inventories, but we also take into account the effects of the fission products which are not present in the initial load of the core.

All these initial safety coefficients are still largely negative for any HN proportion, even if less negative (~25%) than for the ^{233}U-started TMSRs (see Fig. 6). The salt density contribution is equivalent, while the salt heating contribution is less negative because of the presence of Pu instead of ^{233}U.

The feedback coefficients evaluated at equilibrium are equivalent to the results presented on Fig.6 for the ^{233}U-started TMSRs, since these reactors are identical at equilibrium (see paragraph IV.B).

IV.B. Inventories and Waste reduction

Table II. Initial inventories (kilograms) of Th and fissile matter for the Pu-started TMSRs and for the ^{233}U-started TMSRs

HN proportion	^{233}U started TMSR		Pu-started TMSR	
	Th	^{233}U	Th	^{239}Pu+^{241}Pu
7.5%	19760	2550	13850	4887
10%	24050	3105	17560	5524
12.5%	27790	3575	20890	6022
15%	33060	4140	25380	6786
17.5%	37230	4650	29150	7297
20%	42380	5170	33640	7968
22.5%	46100	5580	37040	8378
25%	48640	5820	39320	8668
27.5%	52190	6180	42570	9037

As detailed in Table II, the initial fissile inventories are higher for the Pu-started TMSR than for the ^{233}U-started TMSR, from 20% for the larger HN proportions to 40% for the lower HN proportions. Only the amount of fissile Pu is indicated for the Pu-started TMSRs, the amounts of other transuranic elements used to start the reactor being proportional according to the percentages given in Table I.

The initial inventory in fissile Pu necessary for a Pu-started TMSR ranges from 4 to 8 metric tons, and the Thorium initial inventory from 14 to 42 metric tons.

These reactors being studied to close the current fuel cycle, we have to estimate the reduction of radiotoxicity reached thanks to these TMSRs at equilibrium. We aim at burning all TRUs introduced to start the reactor, so as to have TRU inventories at equilibrium identical to the TRU inventories of ^{233}U-started TMSRs, and this is verified.

Fig.9 shows the burning rate obtained for all the trans-uranic elements after 25, 50, 100 and 200 years of operation. Operation times greater than 60 years (a reactor

lifespan) are obtained by transferring the salt contained in the ending TMSR in a new TMSR. This is made easier thanks to the fact that the fuel is liquid.
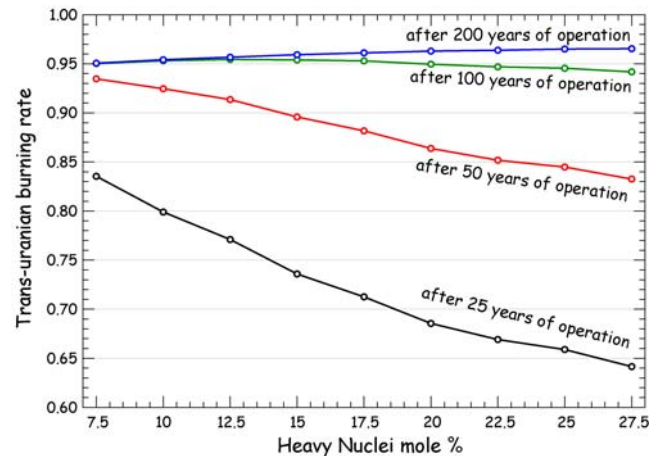

Fig.9. Burning rate of all the transuranic elements after different operation times, as a function of the HN proportion

The lower HN proportion configurations allow faster reductions, since more than 80% of the TRUs are burned after only 25 years of operation, and nearly 95% after 50 years of operation. The larger HN proportion configurations allow higher burning rates, up to 97%, but on the longer run, after more than around 100 years of operation.

Finally, in terms of transuranic inventory, the TMSRs started with Plutonium become equivalent to TMSRs directly started and operated with ^{233}U after around forty years, where more than 85% of the initial TRU inventories are burned, the assets of the Thorium fuel cycle being then recovered.

IV.D. Plutonium Solubility

Pu having a lower solubility limit in a fluoride salt, compared to Uranium for example, this issue has to be examined for the Pu-started TMSRs. Fig. 10 presents the initial mole proportion in the different Pu-started configurations (red line), proportion ranging from 2.5% for the lower HN proportions to 6.5% for the larger HN proportions. According to many studies among which the MSBR studies, it is well attested that the Pu maximum solubility limit in a fluoride salt decreases as the Th proportion increases, deteriorates even faster as Be is added, and is improved if the temperature is increased.

The maximum solubility limit for Pu indicated on Fig. 10 together with its uncertainty (yellow area) give an idea of the typical shape of the solubility limit in a fluoride salt. The lowering of this limit for the smaller HN proportions

is due to the addition of Beryllium in the salt. In our simulations, the maximal Pu solubility limit is reached for the TMSR with 20% of HN in the salt, with no Be added and with the minimal amount of Th in the salt. The reactor configurations with larger HN proportions may encounter Pu solubility problems.
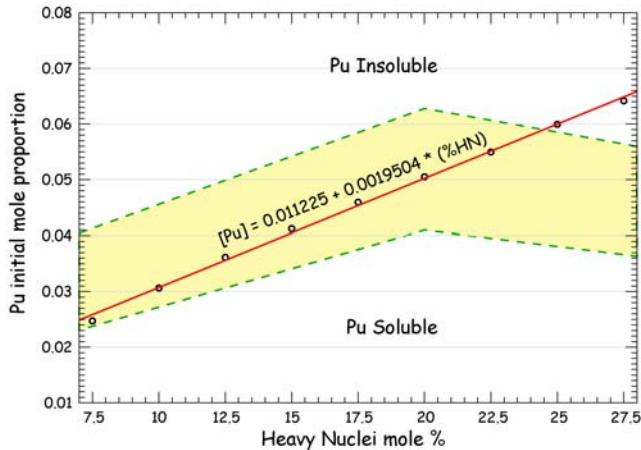

Fig.10. Initial Pu mole proportions in the fuel salt for the different HN proportion configurations (dark dots and red line). The yellow area states for the Pu solubility limit with its uncertainties.

While taking into account the uncertainties on the evaluation of the solubility limit and to be sure not to overshoot this limit, a good compromise could be to slightly increase the reactor operating temperature by around 100 degrees. This allows the use of a fuel salt with no Beryllium and with a lower proportion of HN, and thus a good solubility of Pu.

V. DEPLOYMENT CAPACITIES AND RESOURCES MANAGEMENT

Concerning ^{233}U-started TMSRs, the deployment capacities are based on the amount of ^{233}U produced compared to the initial fissile (^{233}U) inventory necessary to start such a reactor. An example of the amount of ^{233}U produced and extracted all along a TMSR lifespan is presented on Fig. 11 (red line) for a TMSR with 10% of HN in the fuel salt, other TMSR configurations with different HN proportions behaving identically: for TMSRs directly started with ^{233}U, the ^{233}U extraction follows a linear growth, of 37 kg per year in the case shown. This production is directly related to the breeding ratio of the configuration.

Pu-started TMSRs allow the extraction of significantly larger amounts of ^{233}U during the first 20 years of operation (Fig. 11, black line), thanks to the burning of TRUs which saves a part of the ^{233}U produced in the core.

This production reaches 100 kg per year in the example shown, i.e. 60% more than in the corresponding ^{233}U-started TMSR. After the first 20 years, the ^{233}U extraction rate is equivalent to that of the ^{233}U-started TMSR.
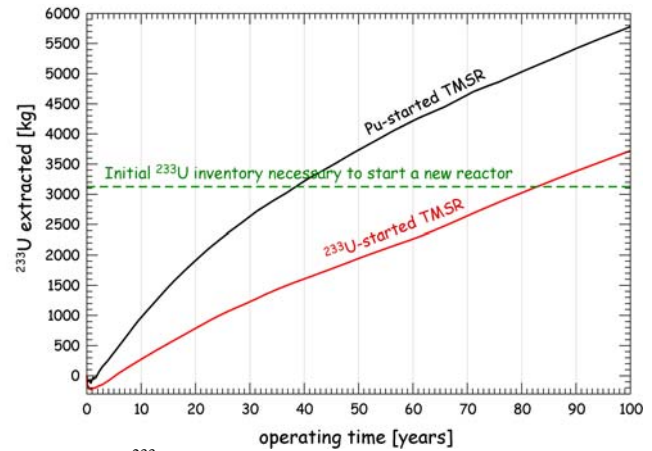

Fig.11. ^{233}U extracted during the operation of TMSR with 10% of HN in the fuel salt

The operating time necessary to produce one initial fissile inventory is called the reactor doubling time. On Fig. 11, the reactor doubling time of a ^{233}U-started TMSR is equal to 83 years and corresponds to the crossing of the ^{233}U production line (red line) with the initial ^{233}U inventory (green dashed line). This reactor doubling time is reduced to 40 years when using Pu in the first load (Fig. 12. dashed line).
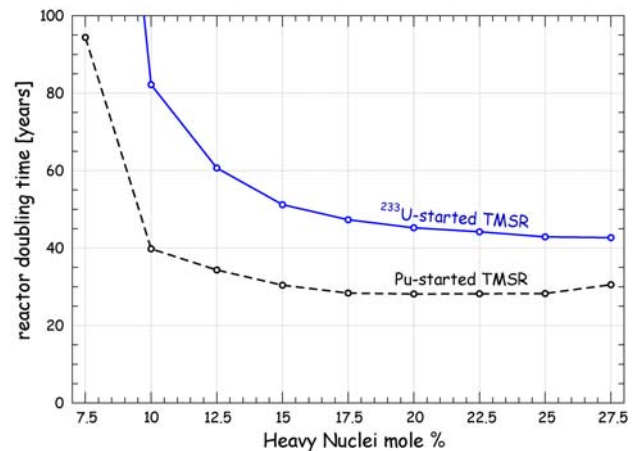

Fig.12. Reactor doubling time of ^{233}U-started (solid line) and Pu-started TMSRs (dashed line) for different HN proportion configurations

To optimize the deployment capacities of a reactor, it first seems logical to minimize the initial fissile inventory, especially in our case where the fissile matter used is not currently available. This means choosing preferably the lower HN proportions. As previously mentioned, a more complete parameter to consider is the reactor doubling

time, which combines this initial fissile inventory constraint with the breeding capacities of the system, i.e. its own capacity to start itself. By generalizing the procedure illustrated on Fig. 11, we thus calculate the reactor doubling times for all HN proportions considered (see Fig. 12). We see again the result detailed on Fig. 11 of a reactor doubling time of 83 years for an HN proportion of 10%.

The higher deployment capacities allowed by the use of TRUs in the Pu-started TMSR are also visible on the reactor doubling times, displayed on Fig. 12 (dashed line), where the configurations with HN proportions larger than 15% have the lower reactor doubling times, around 30 years, to be compared with the doubling times of 45 years reached for the ^{233}U-started TMSRs.
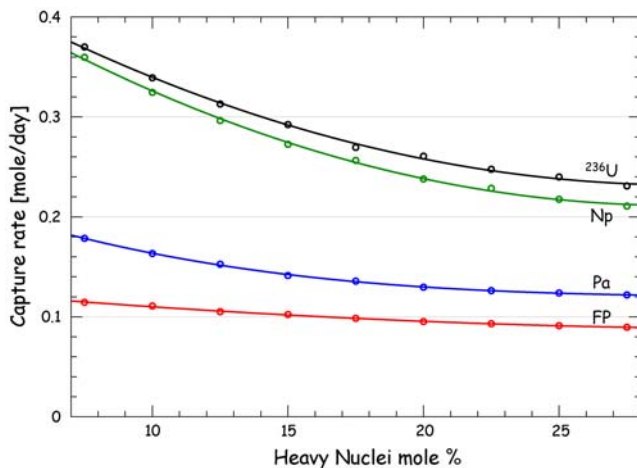

Fig.13. Examples of parasitic capture rates for different components of the fuel salt as a function of the HN proportion

Finally, these configurations with HN proportions larger than 15% have the lowest reactor doubling times and consequently have the best deployment capacities.

These findings that the TMSR configurations with large HN proportions have higher deployment capacities come into conflict with the simple analysis based only on the minimization of the initial fissile inventory, considered at the beginning of this section. Some neutronic behaviors of the core have indeed to be taken into account. For example, for an identical reprocessing, the poisoning of the core by the fission products is relatively more significant for a configuration with a lower HN proportion, as shown on Fig. 13 which presents the values of some parasitic capture rates for different HN proportions. This leads to a reduction of the breeding ratio during reactor operation and finally to smaller deployment capacities for the lower HN proportion configurations.

To conclude this paragraph, the use of Pu and minor actinides to start TMSRs not only allows closing the current fuel cycle but also improves the deployment of such reactors.

VI. CONCLUSIONS

We have presented here a very promising, simple and feasible concept of Molten Salt Reactor with no moderator in the core, operated in the Th/^{233}U fuel cycle, and called non-moderated Thorium Molten Salt Reactor (TMSR).

We have detailed in this article some parametric studies, related to the system reprocessing constraints, and the heavy nuclei composition of the salt which modifies the neutron spectrum of the reactor. We have thus demonstrated the very good characteristics of such reactors, in terms of deterministic safety parameters, waste production, deployment capacities…

Since ^{233}U does not exist on earth and is not being produced today, we have examined a new way to produce ^{233}U directly in standard TMSRs started with the Plutonium and transuranic nuclei produced in the currently operating reactors as fissile matter on a Thorium base, and then operated in the Th/^{233}U cycle. We aimed at designing a critical reactor able to burn the Plutonium and the Minor Actinides produced in the currently operating reactors, and consequently to convert this Plutonium into ^{233}U. This leads to closing the current fuel cycle thanks to these Pu-started TMSRs, i.e. TMSRs started in the Th/Pu fuel cycle, similarly to fast neutron reactors operated in the U/Pu fuel cycle. The burning of transuranic elements in these Pu-started TMSRs results in high waste reduction rates, up to 95-97% for all TMSR configurations evaluated.

We particularly point out in our analyses the excellent level of deterministic safety of all the TMSR configurations studied, for the ^{233}U-started TMSRs as well as for the Pu-started TMSRs.

Finally, to optimize the transition from the second and third generation reactors to the Thorium cycle, we have considered the deployment capacities of each TMSR configuration, combining Pu-started and ^{233}U-started reactors. The main constraint of a sustainable power deployment was the saving of resources, i.e. in our case the higher breeding ratio and the best conversion of Plutonium in ^{233}U. This results in short reactor doubling times, around 30 years, especially for the TMSR configurations containing the proportions of heavy nuclei larger than 15%, i.e. with the faster neutron spectra. Crossing this criterion with the constraint of the Pu solubility, which leads to a preference for TMSR configurations with less than around 20% of heavy nuclei in the salt, the most

promising TMSRs turn out to be the configurations with heavy nuclei proportions ranging from , 15% to 20%, typically 17.5% of heavy nuclei in the fuel salt.
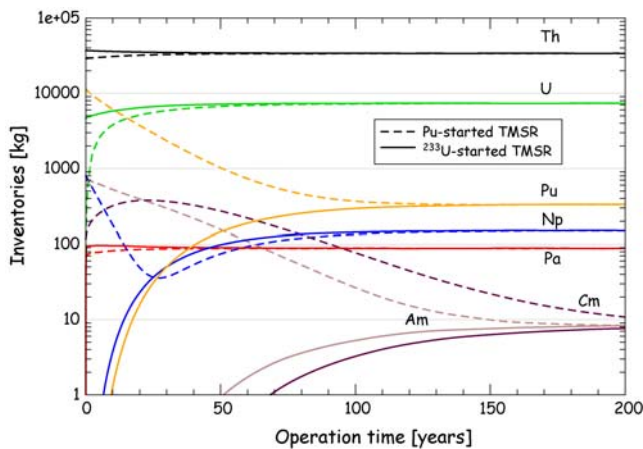

Fig.14. Heavy nuclei inventory for the [233]U-started TMSR (solid lines) and for the Pu-started TMSR (dashed lines)

This typical TMSR configuration contains 4.5 mole % of Plutonium to launch the Pu-started version, with a reactor doubling time of 30 years and a feedback coefficient at equilibrium equal to -7 pcm/K both for the [233]U-started and the Pu-started reactors, allowing a high level of deterministic safety. Fig. 14 illustrates the evolution of the fuel salt composition all along the operation of this reactor, for the [233]U-started (solid lines) and for the Pu-started (dashed lines) TMSR.

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