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Molten Salt Reactors and Possible Scenarios for Future Nuclear Power Deployment

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An important fraction of the future energy demand may be satisfied by nuclear power. In this context, the possibilities of worldwide nuclear deployment are studied. We are convinced that the Molten Salt Reactors may play a central role in this deployment.

The Molten Salt Reactor needs to be coupled to a reprocessing unit in order to extract the Fission Products which poison the core. The efficiency of this reprocessing has a crucial influence on reactor behavior especially for the breeding ratio. The Molten Salt Breeder Reactor project was based on an intensive reprocessing for high breeding purposes. A new concept of Thorium Molten Salt Reactor is presented here.

Including this new concept in the worldwide nuclear deployment, to satisfy these power needs, we consider three typical scenarios, based on three reactor types: Pressurized Water Reactor, Fast Neutron Reactor and Thorium Molten Salt Reactor.

The aim of this paper is to demonstrate, in a first hand that a Thorium Molten Salt Reactor can be realistic, with correct temperature coefficients and at least iso-breeder with slow reprocessing and new geometry; on the other hand that such Molten Salt Reactors enable a successful nuclear deployment, while minimizing fuel and waste management problems.

KEYWORDS: molten salt, Thorium, TMSR, reprocessing, breeding, temperature coefficient, worldwide nuclear deployment, power needs, fissile resources

1 Introduction

Nuclear electricity constitutes an appealing means of covering a significant fraction of the future worldwide energy needs. In this context, Molten Salt Reactors (MSR) are considered as relevant Generation-IV candidates for nuclear power generation expected to start from 2030 on.

The Thorium cycle produces much fewer TRansUranian elements (TRU) than the U/Pu cycle, is based on a more abundant resource, and thanks to its low fissile matter inventory, eases very much a fast nuclear energy deployment. As a consequence, the Thorium Molten Salt Reactor concept has been re-examined. The on-line extraction of Fission Products (FP) is an advantage of the MSR due to its liquid fuel, which allows breeding. With no reprocessing

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at all, the fission chain stops very quickly. As the MSBR's sophisticated reprocessing may appear too ambitious for energy production, we aim at finding some slow reprocessing procedures to obtain a self-breeding system.

Including this new and more realistic reactor concept, we study possible deployment scenarios for a worldwide nuclear energy production. We compare the yields of three main reactor types in regards to the projected energy needs: Pressurized Water Reactor (PWR), Fast Neutron Reactor (FNR) and Thorium Molten Salt Reactor (TMSR). Three main deployment options will be detailed: the "PWR only", the "PWR + FNR", and the "PWR + FNR + TMSR" scenarios.

In this paper, we call 'breeder' a reactor which breeds more fissile materials than it consumes. The 'iso-breeder' appellation corresponds to reactors with a breeding ratio equal to one.

2 Molten Salt Reactor Studies

In a first part, after a description of the MSBR concept, we introduce the new schemes for reprocessing and their impact on the breeding capacity. In the second part temperature coefficients studies and the Thorium blanket solution will be presented.

2.1 The MSBR General Concept

The Molten Salt Breeder Reactor is a concept, developed in the 60's, of a 2500 MWth nuclear reactor based on the molten salt technology [1]. The molten salt, used as fuel and coolant, circulates in a channel network through a graphite matrix as shown on Figure 1 [2]. The MSBR core was split into two zones of moderation differing by the radius of the salt channels. The fuel is a fluoride whose composition is: 70% ^{7}LiF - 17.5% BeF_2 - 12.5% $(HN)F_4$ (where HN means Heavy Nuclide). The initial HN inventory is composed of 1.5% of ^{233}U and 98.5% of ^{232}Th.

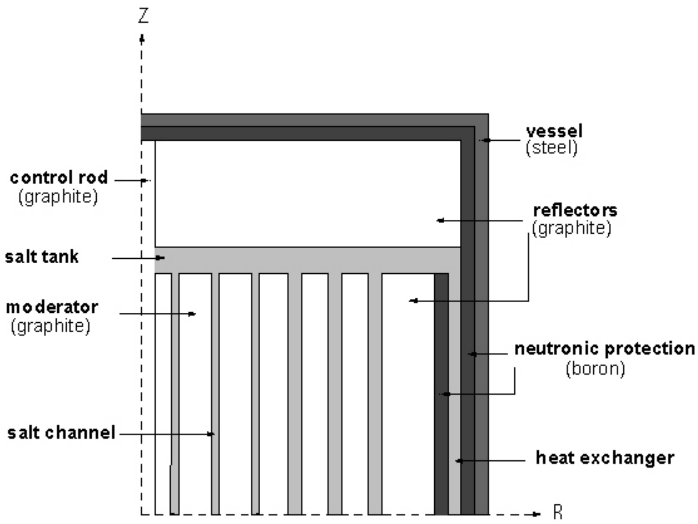


Fig. 1 MSBR vertical slice of the core

Because the fuel is liquid, it can be reprocessed on-line while the reactor continues to operate. In the MSBR concept, the fuel reprocessing considered was sophisticated for a maximum efficiency.

The first step of the reprocessing is the bubbling system whose aim is to quickly remove Fission Products (FPs) like rare gases and noble metals from the salt. The goal of further

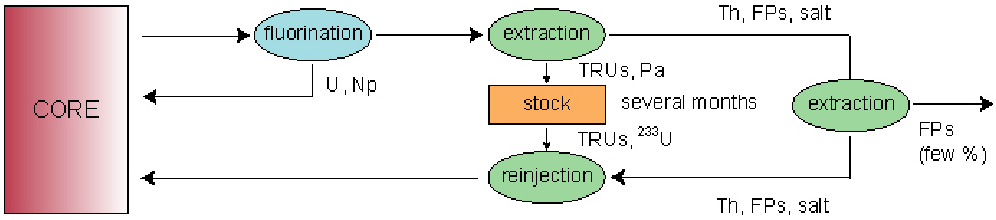


Fig. 2 MSBR reprocessing scheme

reprocessing is to extract FPs from the salt with a liquid/liquid exchanger. As Heavy Nuclides are easier to remove from the salt than FPs, they are previously separated and stored during the FP extraction process, as shown on Figure 2. The full core volume is reprocessed in 10 days which represents about 4 m^3 of salt per day containing 6 tons of Thorium. Extracting FPs from a Thorium fuel is a very difficult issue for the MSBR reprocessing [3].

The temperature coefficient characterizes the evolution of reactivity for a temperature variation. The reactor is considered as unstable if the coefficient is positive since the reactivity would rise with a temperature increase. A recent evaluation of the MSBR shows that its temperature coefficients are slightly positive (between +0.4 and +0.8 pcm/°C [4,5]) contradicting former studies.

2.2 From MSBR to TMSR

The Thorium Molten Salt Reactor (TMSR) is a re-evaluation of the MSBR project. The goal of this project is to define a realistic reactor concept for Generation-IV.

The fuel salt no longer contains Beryllium because of its high level of toxicity. So the salt composition is about 75% ^7LiF - 25% $(HN)F_4$. The melting temperature rises from about 500°C to 570°C but it seems that Hastelloy composing the pipes above the nuclear core can withstand such a temperature increase.

The reprocessing scheme of the MSBR leads to a very high breeding ratio but is too complex to be realistic. The reprocessing can be slowed down from ten days to several hundreds of days. Reprocessing the whole salt volume in 6 months corresponds to a flow of about 200 liters per day containing 300 kg of Th. This flow is low enough to allow Thorium extraction simplifying greatly the subsequent FP extraction. Such a reprocessing scheme is presented on Figure 3.

Most of the solutions considered to solve the temperature coefficient problem involve neutron capture or neutron leakage. These solutions mitigate the breeding while improving the temperature coefficients. A blanket composed of a liquid Thorium salt (75% ^7LiF - 25% ThF_4) set in the place of the radial reflector recovers the escaping neutrons and restores the reactor breeding capacity.

2.3 Slow Reprocessing

Removing the Thorium from the fuel before extracting the FPs solves the usual reprocessing problems and makes the system feasible. The aim of this scheme is to be as general as possible in order to allow for different options. For example the TRUs may be extracted from the salt and managed in another fuel cycle, or may be reinserted in the core to be incinerated. In the same way, Protactinium (Pa) may be removed out of the neutron flux to decay in ^{233}U, or may remain in the core.

The ^{233}U stockpile is the stock of fissile material bred by the reactor. If this stock is negative it represents the needs of ^{233}U to ensure criticality. This stockpile evolves with time and characterizes the breeding performance of the system.

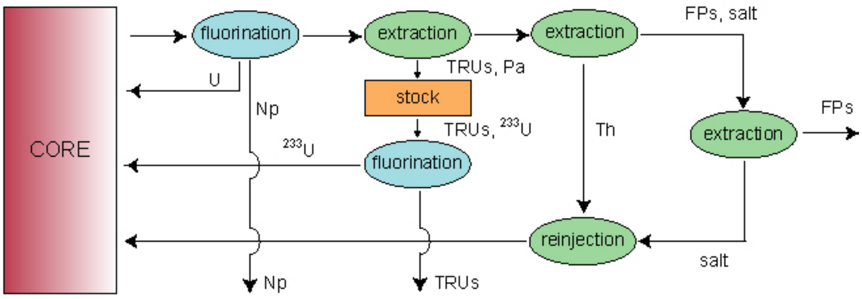


Fig. 3 Slow reprocessing scheme

Figure 4 compares the breeding performance for different reprocessing options. The very effective MSBR reprocessing and the dramatic “bubbling only system” case illustrate two extreme. The three intermediate cases represent the extraction of FPs over a longer time with or without Pa and TRUs extraction. Removing FPs, Pa and TRUs in 6 months is an acceptable reprocessing scheme since the reactor is about iso-breeder. This reprocessing is adopted for our TMSR concept.

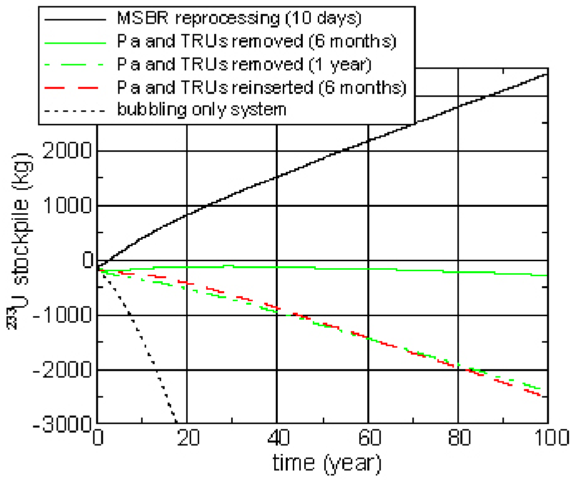


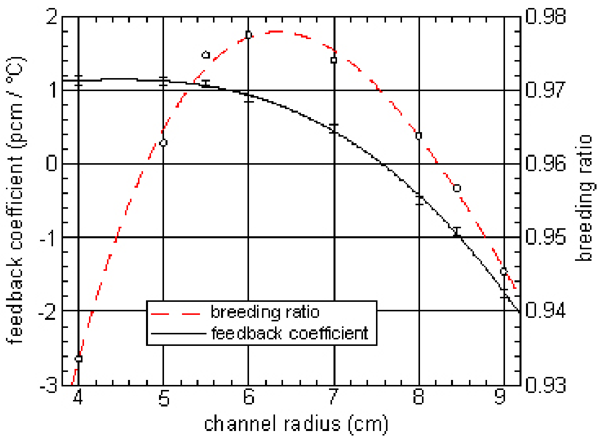
Fig. 4 Fissile materials stockpile for some slow reprocessing schemes compared to the MSBR reprocessing

2.4 The Thorium Blanket

The total temperature coefficient can be split into several coefficients which characterize various physics phenomena. Thus, the Doppler effect, salt dilatation and graphite heating can be studied separately. The total salt coefficient is negative although the dilatation contribution is positive, because of the very negative Doppler coefficient. Graphite heating shifts the thermal part of the spectrum over a shoulder in the ^{233}U fission cross section, so its coefficient is positive.

The reprocessing has a negligible impact on the temperature coefficients, with a total coefficient between +0.2 pcm/°C and +0.5 pcm/°C, depending on whether the TRUs are extracted or not. Minimizing the graphite proportion reduces its coefficient and hardens the spectrum. It improves the Doppler effect but reduces the breeding as shown on Figure 5 (left) [6]. Adding a neutronic poison in the core improves the Doppler (Thorium) or the graphite coefficient (Erbium [7]) but reduces the breeding too. Finally more neutron leakage would be interesting if the escape of neutrons did not lead to a sterile loss.

The only solution which improves both temperature coefficients and breeding is to place Thorium around the core. It recovers any escaped neutrons (from previous solutions) and uses them for the production of fissile material. Moreover the blanket does not act as a reflector and so increases the leakage. To obtain negative temperature coefficients and a breeder reactor configuration we simulate a core with one zone of large salt channels (8.45 cm radius) surrounded by such a blanket. Figure 5 (right) shows the stockpile of ^{233}U for this core compared to the preferred configuration in two zones shown on Figure 4. In all systems, FPs, Pa and TRUs are extracted in 6 months. The stockpile is calculated with and without the blanket breeding in order to demonstrate its impact. The breeding without considering the blanket production is obviously poor because of the salt channel radius (Figure 5 (left)). With the Thorium blanket, total breeding is slightly positive. The reprocessing time may then be adjusted at will, for example to obtain an iso-breeder reactor. It can even be more slowed down at the price of light ^{233}U consumption.



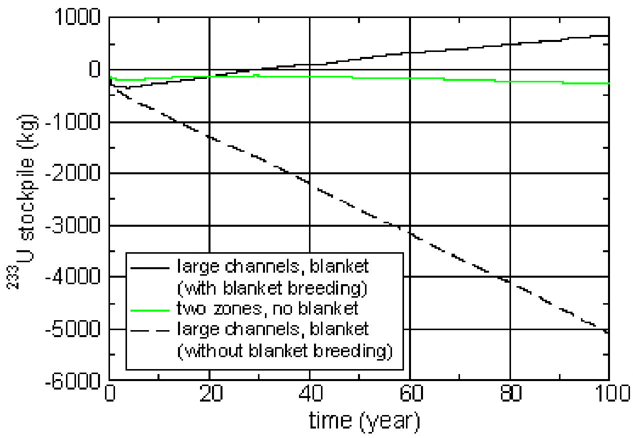


Fig. 5 (left) Impact of the channel radius on the temperature coefficient and the breeding ratio (for a 6 months reprocessing, Pa and TRUs extracted, no blanket) (right) Fissile materials stockpile for different core configurations (with and without Thorium blanket)

Concerning the temperature coefficients, this configuration has large channels so the graphite proportion is lowered, the spectrum is hardened, and leakages are higher. That leads to a coefficient of -0.9 pcm/°C instead of +0.3 pcm/°C for the configuration of Figure 4. With the Thorium blanket, the coefficient is equal to -1.6 pcm/°C, mainly due to a hardening of the spectrum. Indeed, neutrons are captured in the blanket instead of being thermalized by a reflector and that improves the Doppler effect.

The TMSR concept seems workable from a neutronic and chemical point of view. Now it may be included in scenarios studies to evaluate its deployment capacity.

3 Nuclear Power Deployment Scenarios

In this section, we present three possible deployment scenarios for a worldwide nuclear power production. These scenarios are based on three reactor types: the Pressurized Water Reactor (PWR), the Fast Neutron Reactor (FNR), and the TMSR presented above. The details of these reactor types will be introduced as they come up in the simulation.

First, a brief description of the simulation method will introduce our studies. We will then specify the basic data that drive the deployment simulation: the evaluation of the future energetic needs and the natural materials reserve estimates we considered. After that, three main deployment scenarios will be detailed: the "PWR-only" scenario, the "PWR + FNR" scenario, and finally the "PWR + FNR + TMSR" scenario.

3.1 Brief description of the simulation method

The simulation program is driven by the following inputs:

- the timeframe considered for the deployment scenario, i.e. the beginning and ending dates of the scenario;
- the anticipated time evolution of the energy demand;
- the list of the reactor types considered and their priority of utilization;
- the reactor type definitions; for each reactor type, we need to know its launching date, its lifetime, the power generated per unit, the needed fuels, and the inventories i.e. the materials available at reactor unloading, in particular the materials produced during reactor operation;
- the materials available to be used as fuel in the reactors. These include natural resources (Uranium and Thorium) as well as stocks of material produced in some reactor types and consumed in others (Plutonium, Uranium 233, …).

During the simulation, reactors are added once a year, if necessary, to satisfy the prospective energy demand. In addition, a reactor is started only if the fuel needed to cover its operation over the entire reactor lifetime will be available in time. This can imply starting enriching as well as reprocessing units as needed.

Uranium and Thorium natural resource levels, as well as stocks and inventories of materials produced during the running cycle, are monitored all through the scenario. These quantities are also used to evaluate the sustainability of each deployment scenario.

3.2 Basic Data

3.2.1 Evolution of Worldwide Power Needs

Each deployment scenario is driven by a predefined time evolution of anticipated energy demand. Our work is based upon the evolution model of energy needs developed by P-R. Bauquis [8]. In this model, nuclear power generation remains constant between 2000 and 2015; then it increases at a rate of 6.2% per year until 2050, when the production reaches 2600 GWe-year per year, i.e. 7.5 times its current level; finally, a 1.2% annual increase of the production is assumed up to 2150, in order to verify that the scenarios are sustainable.

3.2.2 Natural Resource Levels

The workable natural resources in Uranium are classified considering their costs. The estimation of the final resources in natural Uranium is a function of the technical potentialities and of the extraction costs. Nowadays, the mean extraction cost is at a level of \$30 per kg of Uranium. When considering an extraction cost of \$400 per kgU, the world resources in natural Uranium can be extrapolated to 23 Mtons [9] and this is the Uranium resource level we used in our scenarios.

The resources in natural Thorium are evaluated to be around 2-3 times those of the Uranium resources. As the reactor types we choose are far from running out of Thorium resources, we consider the initial natural Thorium and Uranium resources to be at the same level, in order to simplify the comparison between the two evolutions.

3.3 Deployment Scenarios

3.3.1 "PWR only" scenario

As PWRs represent 75% of the world nuclear power supply, we have first considered the scenario where all the nuclear energy will be produced by this type of reactor.

These reactors operate with thermal neutrons, using light water as moderator and coolant. We have introduced two types of PWRs in our simulation: the current PWR, and a new generation PWR such as the European Pressurized Reactor (EPR) [10]. The characteristics of these reactors are listed in Table 1.

Table 1 Characteristics of the PWR types used in the "PWR only" scenario

	PWR	EPR
Nominal Power (GWe)	1.0	1.45
Load Factor	0.8	0.8
Launching Date	1970	2005
Lifetime	40 years	50 years
Details of the Fuel (per year):		
Type of Fuel	UOX	MOX-UE with Pu multirecycling
Consumed Fuel	27.2 tons	19.7 tons
Fuel Enrichment in ^{235}U	3.5 %	4.5 %
Pu quantity in the Fuel	0 kg	285 kg
Pu produced	270 kg	285 kg
Recovered Uranium after reprocessing	26 tons	18 tons

For the current PWR, the fuel consists of natural enriched Uranium Oxide (UOX fuel). For the future EPR, as there is no other reactor fuelled with the produced Plutonium in this scenario, we choose as fuel a mix of reprocessed Plutonium and enriched Uranium (MOX-UE fuel).

Since the use of natural Uranium reserves can be improved, we set the ^{235}U content of the depleted Uranium rejected by the enriching units of our simulation at 0.1% versus today's 0.25 to 0.3%.

The "PWR only" worldwide deployment scenario and the corresponding evolution of natural Uranium resources are displayed on Figure 6. In this scenario, the electric power produced in 2030 is twice that of today, EPRs replacing the current PWRs. The power installed continues to grow until 2085 with a capacity of 3700 GWe. At this time, the nuclear power generation stops, as a result of the complete exhaustion of the fissile component of the natural Uranium resources. Moreover, this scenario leads to the build up of a stockpile of 4000 tons of Plutonium whose management will entail proliferation problems.

The main conclusion of this scenario is that sustainable nuclear energy production is impossible using only PWRs, as was expected.

Optimal utilization of the Uranium ore is based on the breeding principle: a sustainable development of nuclear energy requires the use of other types of reactor, able to at least breed their fuel. We will consider two such reactors: the Fast Neutron Reactor and the Thorium Molten Salt Reactor.

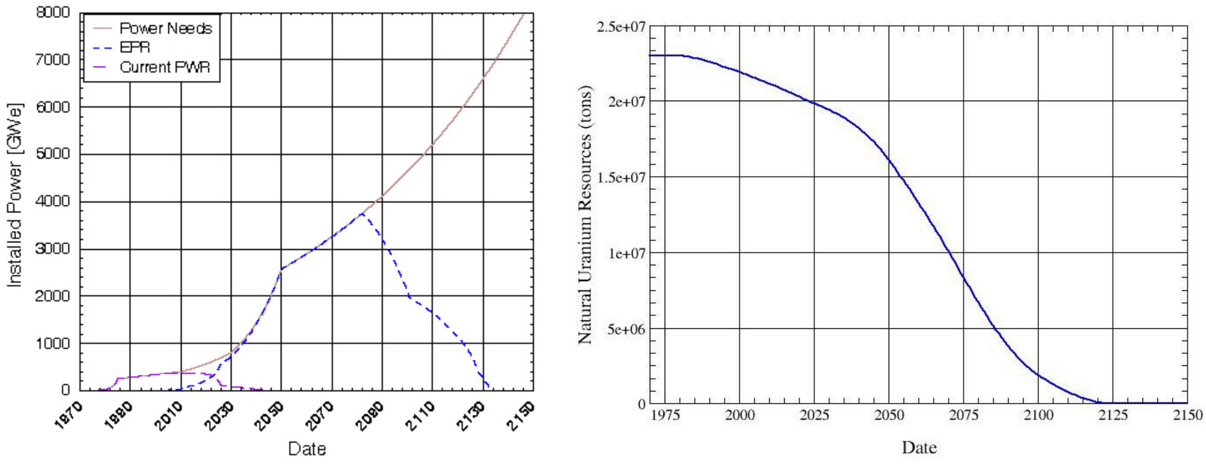


Fig. 6 Power available (left) and Evolution of the natural Uranium Resources (right) in the "PWR only" scenario

3.3.2 "PWR + FNR" scenario

The two types of PWR presented previously, current PWR and future EPR, are used in this scenario, with a difference: the EPRs operate now with UOX fuel, without multi-recycling the Plutonium which will be needed in the FNRs.

Four of the six nuclear systems selected by the Generation-IV international forum are Fast Neutron Reactors. Our study is based on one of these FNRs, studied by the CEA (French Atomic Energy Commission): a liquid metal cooled FNR.

These FNRs are breeder reactors and operate on the U/Pu cycle, fuelled with a mix of Plutonium and depleted Uranium. Their estimated characteristics are listed in Table 2.

Table 2 Estimated characteristics of the FNR type used in the "PWR + FNR" scenario

	Liquid metal cooled FNR
Nominal Power (GWe)	1.0
Launching Date	2020
Lifetime	50 years
Fuel Loading/Unloading Frequency	5 years
Fuel Cooling+Reprocessing Time	5 years
Details of the Fuel (per load):	
Depleted Uranium	48 tons
Plutonium	6 tons
Details of the breeding (per year):	
Depleted Uranium Supply	1 ton
Plutonium Bred	300 kg

The worldwide deployment scenario "PWR + FNR" is shown on Figure 7. The corresponding evolutions of natural Uranium resources and of the stock of Plutonium are displayed on Figure 8.

In this scenario, the stock of Plutonium produced in the PWRs is large enough to start the first FNRs. The FNRs will be dominant from 2075 on and their breeding capacity allows then the full nuclear energy deployment, provided EPRs continue to operate.

The figures showing the material evolutions raise two problems associated to this scenario:

- We observe on Figure 8 the constitution of a stock of 25000 tons of Plutonium in 2150, plus the large amounts of Plutonium corresponding to the fuel inventories of the running FNRs. This large accumulation of Plutonium could cause proliferation difficulties, and this problem cannot be simply resolved by adjusting the FNR breeding rate while satisfying the deployment requirements.
- The Plutonium produced by the PWRs and available before the launching of the first FNRs is not sufficient for an FNR-only deployment. The operation of Plutonium-producing EPRs is necessary all through the scenario, leading to the consumption of 80% of the natural Uranium resources in 2150, as shown on Figure 8. As a consequence, this scenario is not suitable for a sustainable deployment of nuclear power, even though the world power needs can be satisfied in the medium term.

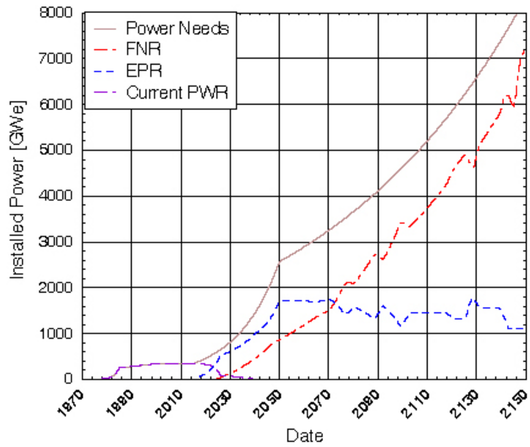


Fig. 7 Power available in the "PWR + FNR" deployment scenario

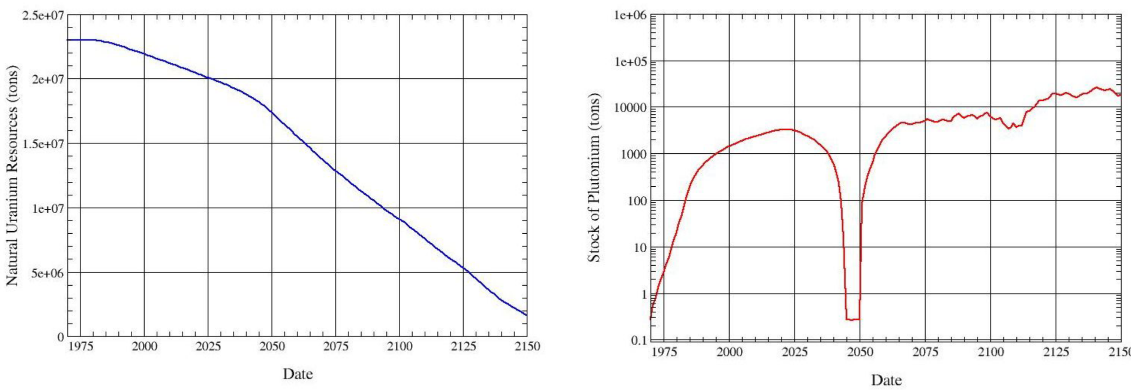


Fig. 8 Evolutions of natural Uranium Resources (left) and of the stock of Plutonium (right) in the “PWR + FNR” scenario

3.3.3 “PWR + FNR + TMSR” scenario

As detailed in the first section of this article, the Molten Salt Reactors we study are based on the $^{232}Th/^{233}U$ fuel cycle. As the fissile material ^{233}U is not naturally available and not even produced in the reactors introduced in the previous scenarios, we have to consider new types of PWRs and FNRs, able to ‘convert’ ^{235}U or Plutonium into ^{233}U. This is possible by adding solid Thorium blankets in the EPRs and FNRs discussed previously. FNRs are now consuming Plutonium and producing ^{233}U. The modified characteristics of these reactors are listed in Table 3. The characteristics of the iso-breeder TMSRs presented in the first section of this paper are summarised in Table 4.

Table 3 Characteristics of the EPR and FNR producing ^{233}U

	EPR with Thorium Blanket	FNR with Thorium Blanket
Type of Fuel	UOX	Depleted Uranium and Plutonium
Fissile material in the fuel	4.9 % (^{235}U)	11 % (Pu)
Details of the inventories (per year):		
Thorium Fuelling	133 kg	500 kg
^{233}U Production	+ 133 kg	+ 500 kg
Plutonium Production	+ 170 kg	- 200 kg

Table 4 Characteristics of the TMSR

	TMSR
Nominal Power (GWe)	1.0
Launching Date	2030
Lifetime	50 years
Details of the Fuel (per unit):	
^{233}U	1.6 tons
Thorium	58 tons
Liquid Thorium Blanket: Thorium Quantity	21 tons

The worldwide deployment scenario “PWR + FNR + TMSR” is shown on Figure 9. The corresponding natural Uranium and Thorium resource evolutions and the stocks of Plutonium and ^{233}U are displayed on Figure 10.

In this third scenario, the electric power produced in 2030 is twice that of today, EPRs and FNRs replacing the current PWRs. In the meantime, the stock of ^{233}U produced both in EPRs and in FNRs is large enough to start the TMSR systems. These TMSRs will be dominant as early as 2040 and, as for the FNRs previously, their breeding capacity allows successful nuclear energy deployment. From 2080 on, EPRs are ending their production. Power generation is assumed by FNRs and TMSRs: the transition to the sustainable systems is over.

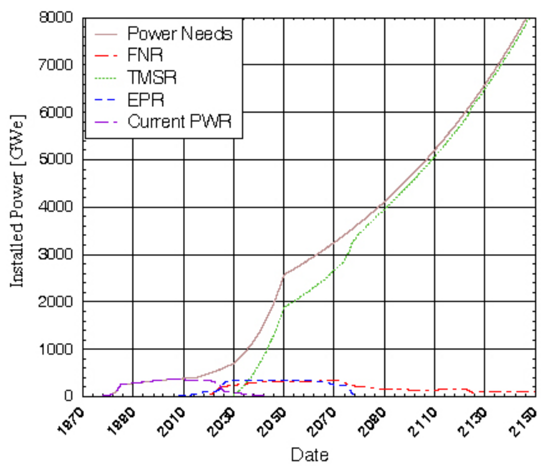


Fig. 9 Power available in the "PWR + FNR + TMSR" deployment scenario

In order to consume the stock of Plutonium produced in the PWRs, we set a higher priority for the start up of an FNR than for a TMSR. As a result, Figure 10 (right) shows that the stock of Plutonium accumulated before the beginning of FNR launching is consumed in 2150. We see on Figure 9 and Figure 10 (left) that the worldwide power needs are satisfied all through the scenario without using up all the natural resources: only a third of the natural Uranium and a negligible part of the natural Thorium resources are necessary for the entire timeframe of the deployment. Assuming a stop of the nuclear energy production, this entire scenario can be restarted at any time, as less than half of the natural Uranium resources are used.

Figure 10 (right) shows a large accumulation of ^{233}U during the deployment. This stock can be reduced according to need by modifying the breeding parameters of the FNRs.

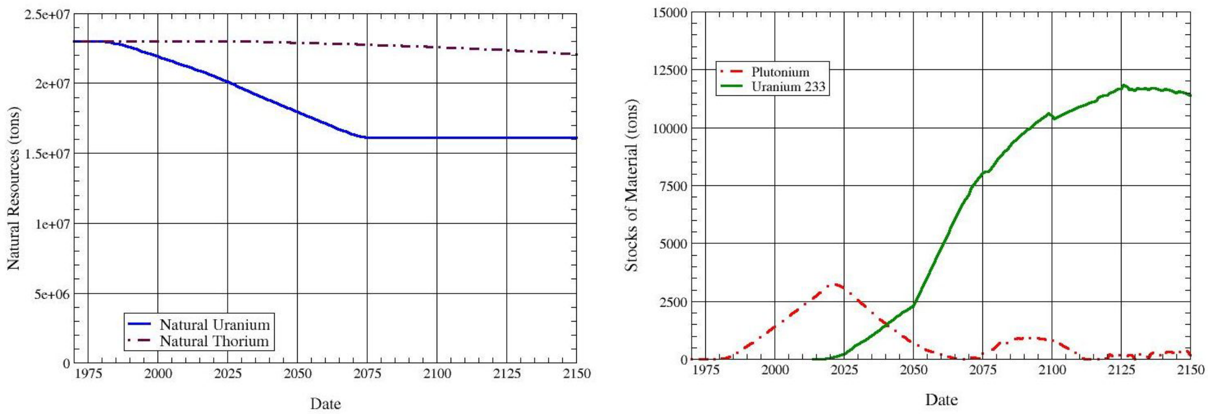


Fig. 10 Evolutions of natural Resources (left) and of the stocks of Plutonium and ^{233}U (right) in the "PWR + FNR + TMSR" scenario

This scenario, which combines the three types of reactor, is by far the most successful, as it fulfils the requirements for a sustainable deployment of the nuclear power production. Finally, to improve the flexibility of this deployment, TMSRs can be set as over-, iso- or under-breeding units according to the amount of ^{233}U needed to make the TMSRs increase, stabilize or stop nuclear power generation.

4 Conclusion

These studies show that it seems possible to define a Thorium Molten Salt Reactor system which is realistic, breeder and with correct temperature coefficient, using the Thorium cycle. With the slow reprocessing scheme, the Thorium can be extracted first and then FPs are removed easily. With the Thorium blanket, breeding can be obtained with negative temperature coefficients. This type of reactor can now be included in nuclear power systems deployment scenarios.

The worldwide nuclear power deployments studied in the second section demonstrate the importance of the TMSR concept: it is only in the “PWR + FNR + TMSR” scenario, where the TMSRs are fuelled by ^{233}U produced in EPRs and FNRs, that a sustainable nuclear power deployment is achieved, while optimizing the fissile material and waste (TRU) stocks. These global scenarios show the limitations on worldwide nuclear power deployment while emphasizing the complementarities in the development of the different reactor types.

This study should be extended to include slower progression of the reactor deployment as well as its local aspects so as to pinpoint possible difficulties linked to the transport of radioactive materials and/or to the risk of proliferation.

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