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Coupled study of the Molten Salt Fast Reactor core physics and its associated reprocessing unit

X. Doligez [a,*], D. Heuer [b], E. Merle-Lucotte [b], M. Allibert [b], V. Ghetta [b]

[a] IPNO-IN2P3-CNRS, Université Paris Sud 11, France
[b] LPSC-IN2P3-CNRS, Université Joseph Fourier, Grenoble-INP, France

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ABSTRACT

Molten Salt Reactors (MSRs) are liquid-fuel reactors, in which the fuel is also the coolant and flows through the core. A particular configuration presented in this paper called the Molten Salt Fast Reactor consists in a Molten Salt Reactor with no moderator inside the core and a salt composition that leads to a fast neutron spectrum. Previous studies showed that this concept (previously called Thorium Molten Salt Reactor – Nonmoderated) has very promising characteristics. The liquid fuel implies a special reprocessing. Each day a small amount of the fuel salt is extracted from the core for on-site reprocessing.

To study such a reactor, the materials evolution within the core has to be coupled to the reprocessing unit, since the latter cleans the salt quasi continuously and feeds the reactor. This paper details the issues associated to the numerical coupling of the core and the reprocessing. It presents how the chemistry is introduced inside the classical Bateman equation (evolution of nuclei within a neutron flux) in order to carry a numerical coupled study. To achieve this goal, the chemistry has to be modeled numerically and integrated to the equations of evolution. This paper presents how is it possible to describe the whole concept (reactor + reprocessing unit) by a system of equations that can be numerically solved.

Our program is a connection between MCNP and a homemade evolution code called REM. Thanks to this tool; constraints on the fuel reprocessing were identified. Limits are specified to preserve the good neutronics properties of the MSFR. In this paper, we show that the limit rate for the reprocessing is 2.5 l of fuel salt a day, which means that the fuel should be reprocessed within 7000 days approximately if there is a specific way to control the redox potential of the salt. Finally, a last part of this paper analyzes the impact of chemical parameter uncertainties on the reprocessing performance.

1. Introduction

Previous studies have shown that a particular configuration of Molten Salt Reactors (MSRs) could be very promising with a fast neutron spectrum (Mathieu et al., 2009; Merle-Lucotte et al., 2008). This configuration has been leading to the concept of Molten Salt Fast Reactor (MSFR) called Thorium Molten Salt Reactor – Nonmoderated (TMSR-NM) in previous works. This kind of reactor should be studied in a different way than solid fuel reactors. Indeed as shown in this paper, the reprocessing is done in situ: a very small proportion of the fuel salt is extracted and reprocessed regularly. Consequently, the coupling between the reprocessing and the core behavior has to be taken into account in order to have a representative simulation of the reactor evolution.

The salt chemistry is a key issue: the salt should be homogenous at any time in any place of the core in order to avoid risks of clogging heat exchangers with insoluble elements. Chemistry properties change during the reactor operation because the element proportions are evolving in the salt. Corrosion in particular, depends exclusively on the red-ox potential, which could be fixed by the uranium III over uranium IV ratio. The aim of this paper is to present a new way to make coupled study of the MSFR core physics and its associated reprocessing unit.

To achieve that goal the calculation of each nuclide proportion evolution during the reactor operation is needed. Two main numerical tools were involved for that purpose: MCNP (Briesmeister, 1997) (which calculates the neutron population at a given time) and a homemade code: REM which solves the evolution equations. An interface between this evolution code and MCNP has been developed, which take into account the reprocessing and the chemistry. This numerical scheme (detailed in Section 3) was previously used and qualified for previous study of MSR in thermal and epithermal neutron spectrum (Nuttin et al., 2005).

* Corresponding author. Address: 15 rue Georges Clémenceau, 91406 Orsay Cedex, France. Tel.: +33 169154494; fax: +33 169154507.
E-mail addresses: doligez@ipno.in2p3.fr, xavier.doligez@gmail.com (X. Doligez).

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The first part of this paper will describe the MSFR concept associated to its reprocessing unit. This unit was designed in order to have a viable model which takes into account all different elements present in the fuel salt (the quasi totality of the Mendeliev table) (Delpech et al., 2009a,b). In a second part the simulation code will be described and special care will be taken with the coupling between neutronics and chemistry. This part explains how the evolution of quantities in each step of the reprocessing unit at any time is calculated, taking into account the core evolution and the chemistry of the reprocessing. The third part of this paper is dedicated to the influence of the reprocessing unit on the core. The impact of the reprocessing parameters on the core behavior is evaluated.

The last part deals with the characterization of the reprocessing unit in terms of heat transfer and risks of criticality. These results are necessary to the viability demonstration and to the assessment of the concept. Finally an uncertainty analysis, focused on chemical data used for the reprocessing, is briefly presented.

2. The MSFR and its associated reprocessing unit

2.1. Description of the core

A Molten Salt Fast Reactor is a Molten Salt Reactor where fuel is a fluoride salt (mix of lithium fluoride, thorium fluoride and uranium fluoride). Consequently the salt is the fuel but also the coolant.

Previous works from CNRS have highlighted a particular configuration of the core which is really a step forward in the Molten Salt Reactor concept (Merle-Lucotte et al., 2009; Heuer et al., 2010). The salt plays three roles simultaneously: fuel, coolant and moderator. A schematic view is shown in Fig. 1: the core comprises a single cylinder whose internal diameter is approximately equal to its height and where the nuclear reactions occur within the flowing fluoride salt. Consequently, in order to maintain three confinement barriers, the vessel should contain all the primary coolant circuit (core, heat exchangers and pumps).

As there is no solid moderator material inside the core, the neutron flux depends only on the proportion of heavy nuclei present in the fuel salt. Previous systematic studies have led us to choose a lithium fluoride salt with 22.5% of heavy nuclei (mostly thorium and fissile material) (Merle-Lucotte et al., 2008).

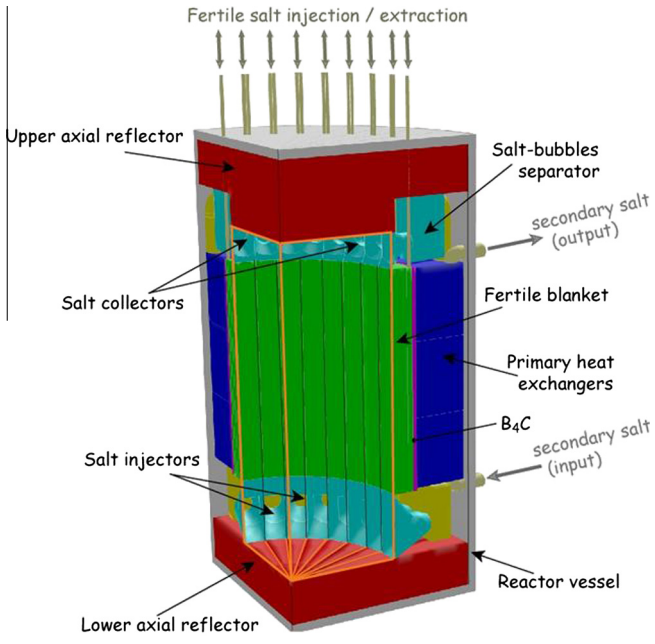

Fig. 1. Molten reactor scheme.

Our simulations are based on a 3 GW thermal power, which corresponds to 1.5 GW electric power with a mean temperature of 700 °C (thermodynamic efficiency of 50%). As shown in reference (Merle-Lucotte et al., 2011) such a MSFR can be started either with uranium 233 or with the transuranic elements produced in pressurized water reactors. Because the results presented in this paper correspond to reactor steady's state, they are independent of the initial fissionable material (the stabilization is not presented here and its study in the reprocessing unit needs further studies). In order to increase breeding ratio, there is a 50 cm thick radial blanket made of lithium fluoride and thorium fluoride. This fertile salt is located in containers made with a nickel based alloy, so this salt is separated from the fuel salt. Table 1 sums-up the principal properties of the MSFR.

2.2. The reprocessing unit

The main goal of the reprocessing unit is to extract all the fission products while keeping all the actinides in the salt as the heavy nuclei are valuable. The reprocessing unit is divided in two different parts: on one hand, there is a "bubbling unit" dedicated to the extraction of insoluble elements as metal and rare gases. On the other hand, a pyrochemical unit performs the lanthanide/actinide separation and extracts the soluble fission products. This is done in situ, on a small amount of the total fuel salt which is extracted regularly from the reactor. The whole process is presented in Fig. 2 and studied in reference (Delpech et al., 2009a,b). The following presents the highlights of this study.

For the insoluble fission products, a bubble injection is foreseen just before the salt injector, and bubbles will be collected just after the core as shown in Fig. 1 (salt-bubbles separator). The gas used for extraction is a mix of helium, krypton and xenon from the core production. The amount of gas injected is around 0.1% of the core volume (7 l of gas per second injected in the fuel salt), hence the core is saturated in gas and the extraction of gaseous fission products is optimized. Those elements are transferred in the injected bubbles. The collected aerosol (containing also metallic particles), very radioactive, is first stocked into a tank during a certain time. At this step, there is a mix of rare gas, noble metals and all daughter nuclei (iodine, bromine, alkali and earth-alkaline elements) because of radioactive decays. After filtration, metallic residues are sent to the waste and the quasi-totality of the gas is sent back into the core. Only the production of gas due to fission has to be extracted – around 2.9 mol per day of krypton, and 3.2 mol of xenon. Consequently, a small proportion (0.017%) of the gas flow injected in the core is extracted from the system and sent to a 3 month storage (which is assumed to be bottle shaped). This storage allows the decay of the xenon isotopes, some of which have decay constant of several days. At the end of this storage, there are only mostly stable isotopes of rare gas and a fraction of Kr-85 (decay constant of 3917 days). Daughter nuclei from radioactive gaseous elements are supposed to be deposited on the storage wall.

Table 1
MSFR characteristics.

Initial salt	LiF(77.5%)–ThF_4(20%)–$^{233}UF_4$(2.5%)
Operating temperature	700–850 °C
Power	3 GW (th)–1.5 GW (elec)
Initial blanket salt	LiF-77.5%; ThF_4-22.5%
Blanket thickness	50 cm
Feedback coefficient	From −5.3 to −4.8 pcm/K
Uranium 233 production	95 kg per year