Annals of Nuclear Energy 64 (2014) 421–429

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Towards the thorium fuel cycle with molten salt fast reactors

D. Heuer, E. Merle-Lucotte *, M. Allibert, M. Brovchenko, V. Ghetta, P. Rubiolo

LPSC-IN2P3-CNRS/UJF/Grenoble INP, LPSC, 53 rue des Martyrs, F-38026 Grenoble Cedex, France

ARTICLE INFO

Article history:
Received 30 December 2012
Accepted 5 August 2013
Available online 7 November 2013

Keywords:
Generation 4 reactors
Molten salt reactor
Thorium fuel cycle
Deployment scenario
Incinerator
MSFR

ABSTRACT

There is currently a renewed interest in molten salt reactors, due to recent conceptual developments on fast neutron spectrum molten salt reactors (MSFRs) using fluoride salts. It has been recognized as a long term alternative to solid-fueled fast neutron systems with a unique potential (large negative temperature and void coefficients, lower fissile inventory, no initial criticality reserve, simplified fuel cycle, wastes reduction etc.) and is thus one of the reference reactors of the Generation IV International Forum. In the MSFR, the liquid fuel processing is part of the reactor where a small side stream of the molten salt is processed for fission product removal and then returned to the reactor. Because of this characteristic, the MSFR can operate with widely varying fuel compositions, so that the MSFR concept may use as initial fissile load, ^{233}U or enriched uranium or also the transuranic elements currently produced by light water reactors. This paper addresses the characteristics of these different launching modes of the MSFR and the Thorium fuel cycle, in terms of safety, proliferation, breeding, and deployment capacities of these reactor configurations. To illustrate the deployment capacities of the MSFR concept, a French nuclear deployment scenario is finally presented, demonstrating that launching the Thorium fuel cycle is easily feasible while closing the current fuel cycle and optimizing the long-term waste management via stockpile incineration in MSRs.

1. Introduction

The Generation-IV International Forum (GIF) for the development of new nuclear energy systems has established a set of goals as research directions for nuclear systems (US DOE, 2002): enhanced safety and reliability, reduced waste generation, effective use of uranium or thorium ores, resistance to proliferation, improved economic competitiveness. Molten Salt Reactors (MSRs) are one of the systems retained by this forum in 2002.

The CNRS has been involved in molten salt reactor studies since 1997. Starting from the Oak-Ridge National Laboratory Molten Salt Breeder Reactor project (Whatley et al., 1970), an innovative concept called Molten Salt Fast Reactor or MSFR (Nuttin et al., 2005; Mathieu et al., 2006, 2009; Forsberg et al., 2007; Merle-Lucotte et al., 2008, 2009a,b) has been proposed. This concept results from extensive parametric studies in which various core arrangements, reprocessing performances and salt compositions were investigated with a view to the deployment of a thorium based reactor fleet on a worldwide scale. The primary feature of the MSFR concept versus that of other older MSR designs is the removal of the graphite moderator from the core (graphite-free core), resulting in a breeder reactor with a fast neutron spectrum and operated in the Thorium fuel cycle, as described in Section 2 of this paper. The MSFR has been recognized as a long term alternative to solid fueled fast neutron systems with a unique potential (excellent safety coefficients, smaller fissile inventory, no need for criticality reserve, simplified fuel cycle etc.) and has thus been officially selected for further studies by the Generation IV International Forum as of 2008 (GIF, 2008, 2009; Boussier et al., 2012; Renault et al., 2009).

In the MSFR, the liquid fuel processing is an integral part of the reactor where a small sample of the molten salt is set aside to be processed for fission product removal and then returned to the reactor. This is fundamentally different from a solid-fueled reactor where separate facilities produce the solid fuel and process the Spent Nuclear Fuel. The MSFR can be operated with widely varying fuel compositions thanks to its on-line fuel control and flexible fuel processing: its initial fissile load may comprise ^{233}U, ^{235}U enriched (between 5% and 30%) natural uranium, or the transuranic (TRU) elements currently produced by PWRs. The characteristics (initial fissile inventory, safety parameters, and deployment capabilities) of each of these MSFR starting modes are detailed in Section 3, while the transition from today's second and third generation reactors to the Thorium fuel cycle is illustrated in Section 4 through the deployment capacities of a MSFR park in the context of France.

---

* Corresponding author. Tel.: +33 476284150.
E-mail address: merle@lpsc.in2p3.fr (E. Merle-Lucotte).

0306-4549/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.anucene.2013.08.002

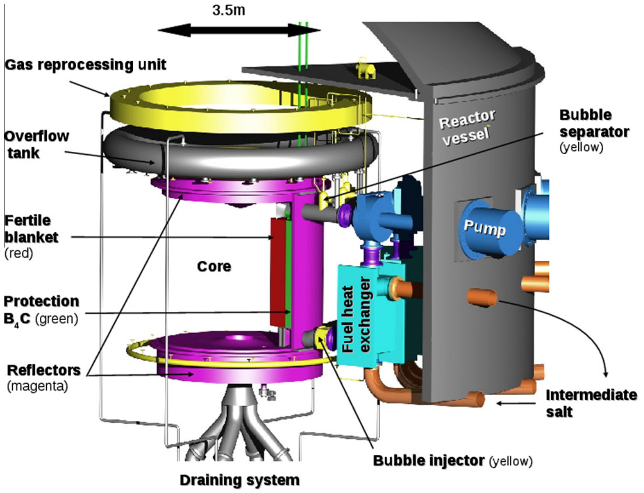

Fig. 1. Pre-design of the fuel salt circuit of the MSFR.

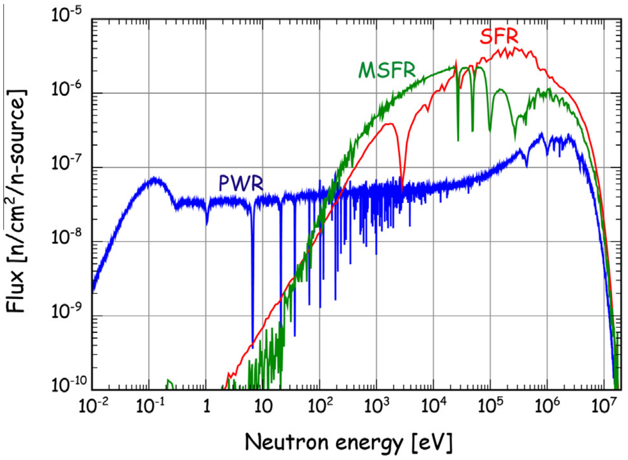

Fig. 2. Fast neutron spectra of the reference MSFR (green curve) and of a sodium-cooled fast neutron reactor (SFR – red curve) compared to the thermalized spectrum of a pressurized water reactor (PWR – blue curve). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Molten Salt Fast Reactor (MSFR) concept

2.1. System description

The standard MSFR is a 3000 MWth reactor with a total fuel salt volume of 18 m^3, with a mean fuel temperature of 750 °C. In order to allow exploration and discussions on possible ranges for physical and chemical parameters, basic drawings have been worked out in relation to the calculations. Fig. 1 describes one of the optimized geometrical configurations of the system. The core consists of a compact cylinder (height/diameter ratio =1) where the liquid fluoride fuel salt flows freely from the bottom to the top of the central component with no solid moderator. The return circulation of the salt (from the top to the bottom) is fragmented into 16 groups of pumps and heat exchangers located around the core (Brovchenko et al., 2012). The fuel salt completes a full cycle in 3–4 s. At any time, half of the total fuel salt volume is in the core and half in the external fuel circuit (salt collectors, salt-bubble separators, fuel heat exchangers, pumps, salt injectors and pipes).

The MSFR simulations have been performed using a binary fluoride salt, composed of LiF enriched in ^{7}Li to 99.995% and a heavy nuclei (HN) mixture initially composed of fertile thorium and fissile material, ^{233}U, $^{\text{enriched}}$U and/or Pu and minor actinides. The (HN)F_4 proportion is set at 22.5 mol% (eutectic point), corresponding to a melting temperature of 565 °C. The choice of this fuel salt composition rests on many systematic studies (influence of the chemical reprocessing on neutronic behavior, burning capabilities, deterministic safety level, deployment capabilities) (Merle-Lucotte et al., 2009a,b, 2012).

This salt composition leads to a fast neutron spectrum in the core, as shown in Fig. 2 where the fast neutron spectrum of the simulated reference MSFR is compared to the spectra of 2 solid-fuel reactors: a Sodium-cooled Fast neutron Reactor (SFR) and a thermal Pressurized Water Reactor (PWR). The large Na capture cross-section appears clearly on the red curve at 2.8 keV, while the inelastic scattering cross-section of fluorine shows on the green curve between 0.1 MeV and 1 MeV.

The external core structures and the fuel heat exchangers are protected by thick reflectors made of nickel-based alloys, which have been designed to stop more than 99% of the escaping neutron flux. The radial reflector includes a fertile blanket (50 cm thick-red[1] area in Fig. 1) to increase the breeding ratio. This blanket is filled with a fertile salt of LiF–ThF_4 with initially 22.5 mol% of ^{232}Th. This blanket is surrounded by a 20 cm thick layer of B_4C, which provides protection from the remaining neutrons.

One advantage of a liquid fuel is that its configuration can be modified with no fuel handling, simply by passively draining the fuel salt by gravity into tanks located below the reactor. Two fuel configurations are thus available with no external intervention:

1. the fuel configuration in the reactor, optimized for heat production, corresponding to the critical core;
2. the fuel configuration in the draining tanks, designed to optimize heat and neutron evacuation. This is a sub-critical configuration that allows passive and active heat extraction. In PWR parlance, this is equivalent to a hot shutdown with subsequent removal of the fuel to the fuel building after a few days.

During normal reactor operation, this draining procedure will lead to MSFR shutdown, sub-criticality being reached quickly and easily. In case of an accident or incident leading to a loss of heat sink, the fuel will still be cooled in the draining tanks, the residual decay heat being thus extracted within months.

Fuel salt cleaning (Delpech et al., 2009; Ghetta et al., 2010; Doligez, 2010) involves two processes: (1) the mechanical extraction of rare gases and some noble metals via an on-line bubbling process; (2) the removal of other fission products via batch processing of small fuel salt samples (typical rate ~10–40 l/day) at an on-site facility near the reactor.

2.2. Simulation tools and methodology

Our numerical simulations rely on the coupling of the MCNP neutron transport (Briesmeister, 1997) with a home-made materials evolution code REM (Heuer et al., 2010; Doligez et al., 2009; Nuttin, 2002; Matthieu, 2005).

The probabilistic MCNP code evaluates the neutron flux and the reaction rates in all the parts (called cells) of the simulated system. This requires a precise description of the geometry and the characteristics of all materials involved (temperature, density, elements, isotopes, proportions), together with the interaction cross-sections of each isotope present in the reactor.

---

[1] For interpretation of color in Figs. 1 and 6, the reader is referred to the web version of this article.