Progress in Nuclear Energy 103 (2018) 28–32

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Construction of minor actinides reduction scenario in Japan utilizing fusion reactors

Yuki Furudate, Hiroki Shishido*, Noritaka Yusa, Hidetoshi Hashizume

Department of Quantum Science and Energy Engineering, Graduate School of Engineering, Tohoku University, 6-6-01-2 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-8579, Japan

ARTICLE INFO

Keywords:
High-level radioactive waste
Partitioning and transmutation
Fusion neutron
Helical reactor
Monte Carlo simulation
Burn-up simulation

ABSTRACT

This study demonstrates by numerical simulations how transmuting minor actinides in fusion reactors can contribute to nuclear fuel cycles in Japan. Minor actinides are installed into blankets of a helical-type fusion reactor to transmute them rather moderately so that neither large neutron wall loading nor removal of large heat are required. Neutron transport and burn-up simulations are conducted to optimize the position of minor actinides and the blanket's structure for transmutation. Whereas the ratio of transmuted minor actinides is not large, the total amount of transmuted minor actinides is revealed to be sufficient because of the system's large inventory. The simulations are followed by a plan that introduces fusion reactors intended for transmutation. Discussion based on Japan's present situation confirms that introduction of fusion reactors with a thermal fusion output of 1 GW by the year 2050 would mitigate many issues concerning disposal of high-level radioactive waste.

1. Introduction

In nuclear energy use, disposal of high-level radioactive waste is a high-priority issue. Minor actinide (MA) nuclides contained in spent nuclear fuel are of particular concern because of their long-term radiotoxicity. Partitioning and transmuting MA is presently regarded as an effective method to address this issue (Magill et al., 2003; Salvatores, 2005). The most efficient way to transmute MA nuclides into stable or short-half-life ones is to cause fission reactions, and such studies have been reported since almost the beginning of the use of nuclear energy (Claiborne, 1972; Wolkenhauer et al., 1973). Although neutron sources are proposed to transmute MA such as fast reactors (Inoue et al., 1991), accelerator-driven systems (Bowman, 1998; Tsujimoto et al., 2004) and fusion reactors (Parish and Davidson, 1980; Peng and Cheng, 1993), neutrons generated by fusion reactors are most preferred for transmutation because of their high energy (14.06 MeV) and monochromaticity. This is because MAs' (n, fission) cross sections become larger than those of (n, γ) cross sections only against neutrons with an energy larger than approximately 1 MeV. Furthermore, the ratio of (n, fission) cross sections against (n, γ) cross sections for 14.06 MeV neutrons is several tens of times larger than that for 2 MeV neutrons.

Many studies have demonstrated the effectiveness of tokamak-type fusion reactors to transmute MA by numerical simulations (Feng and Zhang, 2003; Hong and Moon, 2014; Kotschenreuther et al., 2009; Stacey, 2009; Wu and FDS Team, 2006). Most of these studies have assumed high neutron wall loading and dense MA loading into blankets to transmute MA effectively. In contrast, however, large neutron wall loading is not preferable from the viewpoint of blanket design. Because transmuting MA, especially by fission reaction, generates heat as well, designing a blanket system that transmutes MA effectively is a significant challenge to the engineering design of the blanket system.

Based on the background above, this study proposes to transmute MA rather moderately, namely with a low fission reaction rate. This study performs neutron transport and burn-up simulations by assuming the design of a realistic helical fusion reactor FFHR-d1 (Sagara et al., 2014) equipped with a liquid blanket systems. This is because the assumption leads to a realistic discussion and also liquid blanket systems are favorable for loading and removing MA due to their continuous operation. In addition, liquid blanket systems would enable to quickly remove loaded MA in case of accident using the gravity force. The MA loading position is far away from the core plasma, which has relatively lower neutron wall load and heat flux to avoid imposing severe engineering challenges on the system design. Whereas the ratio of transmuted MA to the total amount of loaded MA is not particularly large, the total amount of transmuted MA is revealed to be sufficient because of the large MA inventory in the system. Subsequently, a transmutation scenario introducing the fusion reactor is proposed.

* Corresponding author.
E-mail address: hshishi@karma.qse.tohoku.ac.jp (H. Shishido).

https://doi.org/10.1016/j.pnucene.2017.11.003
Received 14 June 2017; Received in revised form 1 November 2017; Accepted 2 November 2017
Available online 09 November 2017

2. Materials and methods

2.1. Amount of MA in Japan

The total amount of spent nuclear fuels accumulated by light water reactors in the past is estimated to be 17,000 tons. According to the nuclides composition database of the spent nuclear fuels (Ando and Takano, 1999), the amount and composition of MA contained in the spent nuclear fuels differs depending on the reactor type, fuel type, fuel burnup, and cooling time. Based on these data, the amount of MA that accumulated in year 2010 is calculated to be 30 tons. In addition, the operational situation of nuclear power plants in the future of Japan is assumed to be as follows. Two nuclear power plants start operation every year from years 2015–2039. The permitted output and capacity factor, which is the ratio of the net electricity generated to the energy full-power operation generates, of each reactor are assumed to be 1 GWe and 70%, respectively. A reprocessing plant will start operation in year 2020 and its annual capacity is assumed to be 800 tU/year (tonnes uranium per year); thus the amount of MA recovery from the spent nuclear fuels is approximately 1.6 ton/year. The accumulation of MA can be calculated under these assumptions—50 tons of MA will be available by year 2050.

2.2. MA loading positions

In the designing of the helical-type fusion reactor FFHR-d1, the breeding blankets are classified into two regions: one inside the helical coils where the blanket is next to the core plasma and another facing the cross-over point of the magnetic surfaces where the blanket is comparatively distant from the core plasma (Goto et al., 2016). At the region distant from the plasma, sufficient neutron flux (< 2 MW/m^2) can be secured (Tanaka et al., 2014) with relatively lower heat flux than the region inside the helical coils. Fig. 1 shows that a poloidal range of 30° is assumed for the irradiated region and also for the loading region. In the event of a severe accident, loaded MA needs to be quickly extracted from the reactor and the loading position is limited on the downside of plasma considering the use of gravity force. Then, 10 loading positions are secured in one helical-type fusion reactor that has five helical pitches designed in FFHR-d1.

These loading positions overlap with ports for periodic replacement of breeding blankets and divertors; therefore, the reprocessing and modifying of MA are available concurrently. A fusion reactor is modeled as a torus with a major and minor radius of 14.0 m and 5.0 m, respectively. A minor radius of 5.0 m was decided according to the maximum distance from the core plasma to the blanket first wall.

2.3. Methods and conditions

This study first evaluates the capability of a fusion reactor to transmute MA nuclides by neutron transport and burn-up simulations.

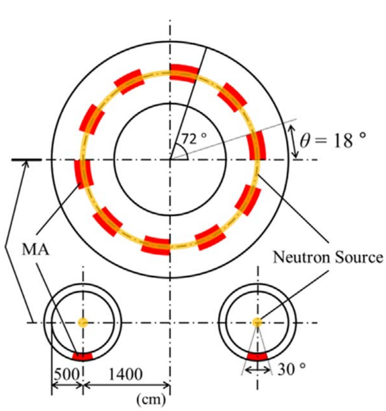

Fig. 1. Overview of 10 MA loading positions and circular neutron source.

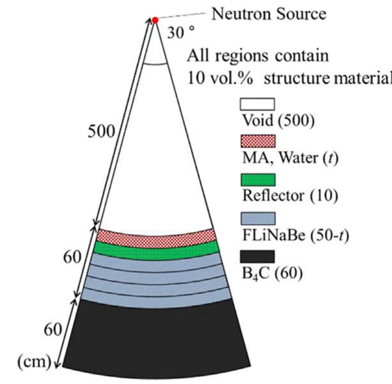

Fig. 2. Poloidal cross section of MA loading position (case of t = 10 cm) showing the arrangement of the 10-cm neutron reflector.

The simulation domain is only one of 10 loading positions and the toroidal range of the neutron source was determined to be the same range as the MA loading range θ [°] to take into account the neutron shading effect of the inner blanket. This effect significantly functions in the toroidal direction due to the high-pitch helical configuration, so that the neutron source contributing to the MA transmutation is limited to the immediate vicinity of the loading position.

Fig. 2 illustrates the poloidal cross section of one loading position used in simulations, and Table 1 summarizes the conditions of simulations. The simulations assume that MA is loaded in a nitride state because of its high MA density and good thermal properties (Minato et al., 2003). The loading position is filled with water that acts as coolant around the MA nitride. In the blanket region, except at MA loading positions, molten salt FLiNaBe (^{6}Li molar ratio is 90%), which is proposed for use in FFHR-d1 as a tritium breeder and coolant, is situated. Whole blanket regions are covered by the shielding material B_4C. All regions homogeneously contain 10 vol% of structure material JLF-1. The total amount of MA available by year 2050 in Japan is assumed to be 50 tons and because there are 10 positions to load MA, such that 5 tons of MA are loaded into one position. The composition of MA assumed in the simulations is summarized in Table 2, which is based on UO_2 fuel from pressurized water reactors with burnup of 45 GWd/tU and cooling of 5 years.

The simulations evaluate the effect of toroidal range θ [°] and thickness t [cm] of loading position on transmutation performance. Situating neutron reflectors made of graphite or lead at the rear of the loading position is also considered. Based on the results of these simulations, optimum conditions of MA loading position and neutron reflector are selected for application to subsequent simulations that evaluate the effect of the fusion output of the reactor and the MA composition, which changes over time owing to the influence of transmuting and annual reloading. Especially, short-half-life nuclides such as ^{244}Cm, having a half-life of 18.1 years, affect the composition

Table 1
Simulation conditions.

Fusion output (GW)	1, 2, 3
MA composition	Containing ^{244}Cm, Excepting ^{244}Cm
Loading thickness t (cm) [a]	3, 5, 7, 10, 15, 20
Toroidal range of loading position and neutron source, θ (°)	18, 36
Reflector material (Density, g/cm^3)	Graphite (2.26), Lead (11.0), None

[a] Minimum loading thickness for a 18° toroidal range is 5 cm, such that 5 tons of MA loading is possible.