Fusion Engineering and Design 89 (2014) 2523–2528

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Transmutation characteristics of minor actinides in a low aspect ratio tokamak fusion reactor

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HIGHLIGHTS

- Optimum radial build for the LAR tokamak transmutation reactor through the self-consistent calculation.
- Dependence of the transmutation characteristics on the aspect ratios.
- Additional effects of Pu239 in transmutation blanket for minor actinides destruction.
- Transmutation of the minor actinides using by a compact transmutation reactor based on the LAR tokamak.

ARTICLE INFO

Article history:
Received 19 June 2013
Received in revised form 14 April 2014
Accepted 30 May 2014
Available online 1 July 2014

Keywords:
Transmutation reactor
LAR tokamak
Minor actinides
BISON-C
Systems analysis

ABSTRACT

The transmutation characteristics of minor actinides in the transmutation reactor of a low aspect ratio (LAR) tokamak are investigated. One-dimensional neutron transport and burn-up calculations coupled with a tokamak systems analysis were performed to determine optimal system parameters. The dependence of the transmutation characteristics, including the neutron multiplication factor, produced power, and the transmutation rate, on the aspect ratio *A* in the range of 1.5–2.0 was examined. By adding Pu239 to the transmutation blanket as a neutron multiplication material, it was shown that a single transmutation reactor producing a fusion power of 150 MW_{th} can destroy minor actinides contained in the spent fuels for more than 38 units of 1 GW_e pressurized water reactors (PWRs) while producing a power in the range of 1.8–6.8 GW_{th}.

1. Introduction

In order to destroy high-level waste from spent pressurized water reactor (PWR) fuel, the transmutation of long-lived radioactive actinides into short-lived and stable isotopes using a fission reactor, an accelerator driven system, and D-T fusion neutrons has been studied so as to reduce the long-term toxicity levels of nuclear waste [1–5]. Thermal fission approaches to destroy Pu and minor actinide (MA) isotopes in a fusion reactor have been also explored [2–5]. The transmutation of high-level waste through the utilization of D-T fusion neutrons will provide a viable application of fusion before its essential purpose of power production. Minor actinides can be separated from other nuclear waste based on an appropriate waste management strategy and thus, a feasibility study of the transmutation of minor actinides by a fission reaction with 14 MeV fusion neutrons in a low aspect ratio (LAR) tokamak is very important. In a tokamak fusion device, an aspect ratio is defined as a ratio of a major radius to a minor radius. As a 14 MeV neutron source, the LAR tokamak is a viable option since it combines a compact tokamak reactor with plasma having a large elongated shape which is a favorable shape for a transmutation reactor. In order to destroy as much of the waste as possible while minimizing its overall size, the neutron source based on the LAR tokamak must be optimized. The sub-critical reactor concept is preferred in terms of reactor safety [6].

For the optimal design of a LAR tokamak neutron source, the radial build of the reactor components must be determined in order to satisfy all plasma physics and engineering constraints. Therefore, in this work we assume that the constraints are the same as those used in the design of the international thermonuclear experimental reactor (ITER). In a transmutation reactor, a blanket should produce enough tritium for tritium self-sufficiency, while the neutron multiplication factor k_{eff} should be less than 1.0 to maintain sub-criticality. Hence, the key objective in the neutronic design is to obtain a higher transmutation rate via optimization of the neutron energy spectrum, the inventories of actinides, and the thickness

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http://dx.doi.org/10.1016/j.fusengdes.2014.05.029

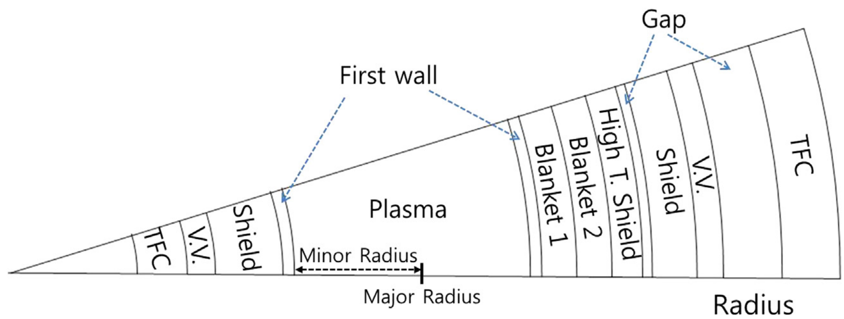

Fig. 1. Radial build of a transmutation reactor.

of the transmutation blanket. A shield should provide sufficient protection for the superconducting toroidal field (TF) coil against radiation damage and nuclear heating induced by both fusion and fission neutrons. For this purpose, we coupled the systems analysis [7] with one-dimensional neutron transport analysis, and the concept of the transmutation reactor based on the LAR tokamak was developed with an aspect ratio A in the range of 1.5–2.0.

In this work, the transmutation characteristics of minor actinides in a LAR tokamak transmutation reactor with a neutron wall loading of less than l.0 MW/m^2 were investigated. In order to obtain a higher neutron flux and improve the transmutation rate, Pu239 was chosen as a neutron multiplication material, and its effect on the transmutation characteristics was studied. In Section 2, the optimal system parameters of the LAR tokamak transmutation reactor are discussed with A in the range of 1.5–2.0. The transmutation characteristics of the minor actinides are then examined for three different aspect ratios, and the results are outlined in Section 3. Finally, a summary of our findings is provided in Section 4.

2. Concept of a LAR tokamak transmutation reactor

The system parameters of the transmutation reactor must satisfy all plasma physics and engineering constraints. Such constraints are in turn related to various system parameters. In this work, we assumed that the constraints were on the same technological level as those in the design of the ITER. Furthermore, we coupled the tokamak systems analysis [7] with one-dimensional neutron transport and burn-up calculations for the self-consistent determination of system parameters. BISON-C [8] with a 42 neutron group cross section library based on JENDL-3 was employed for the one-dimensional neutron transport and burn-up calculations [9], while the JENDL-3 dosimetry file was used for estimations of the local tritium breeding ratio (TBR). In the BISON-C code, the one-dimensional neutron transport equation was solved to obtain the neutron flux, and the nuclide production-depletion equations were solved using the obtained flux and the burn-up library. We note that, after the scoping study based on the systems analysis and one-dimensional transport calculations, more accurate computations of quantities such as k_{eff}, the radiation damage to plasma-facing components, and the tritium breeding capability of the blanket using multi-dimensional analysis must be performed with the selected concept of the transmutation reactor.

The radial build of the LAR tokamak transmutation reactor was modeled in a cylindrical geometry, as shown in Fig. 1. Neutron transport calculations were performed with the same geometry under the assumption of an isotropic neutron distribution. There was no inboard blanket in the inboard region because tritium self-sufficiency could be satisfied with the proper choice of an inboard shield material in the LAR tokamak [10]. The material composition of the reactor components is listed in Table 1. Consistent with current ITER technology, water was selected for cooling all reactor components except for the blankets, and an Nb_3Sn superconductor was used as the toroidal magnetic field coil. In addition to the current density and maximum toroidal magnetic field at the inner leg of the TF coil, neutron damage to the superconductor should be taken into account to determine the radial build. The vacuum vessel was assumed to be made of 0.15 m-thick borated stainless steel cooled by water. The shield was composed of WC cooled by water. Sufficient space for the shield should be required to protect the superconducting TF coil against nuclear heating and radiation damage [10]. With the lifetime of the neutron source assumed to be 40 years at 75% availability, the fast neutron fluence on the superconductor should be kept below 10^{19} n cm^{-2} for Nb_3Sn, the displacement damage to the Cu stabilizer should be below 5×10^{-4} dpa, and the dose should be lower than 10^9 rad for the organic insulators.

Table 1
Material composition of a transmutation reactor.

Component	Material composition (vol.%)
Vacuum vessel	Borated steel (60), H_2O (40)
Shield	WC (80), H_2O (20)
High temperature shield	WC
Blanket 1	MA_2O_3 (50), SUS316 (15), He (35)
Blanket 2	SUS316 (7), PbLi (90), SiC (3)
First wall	SUS316 (60), H_2O (40)

As seen in Fig. 1, blankets 1 and 2 have different functions and thus, they can be managed separately. In blanket 1, the minor actinides are loaded for transmutation. SUS316LN coated with SiC is used as a structural material, and helium is employed as a coolant in blanket 1. Blanket 2 is used for tritium breeding, where SUS316LN coated with SiC is utilized as the structural material, PbLi as the coolant, and tritium as the breeding material. By placing the tritium breeding blanket after the transmutation blanket, tritium self-sufficiency can be easily satisfied due to the abundance of neutrons produced by fission of the minor actinides. Therefore, natural Li can be employed, while the enrichment of Li-6 is necessary to satisfy the tritium self-sufficiency requirement in the fusion reactor [10]. The first wall with a thickness of 3 cm is made of SUS316LN cooled by water.

The system parameters of the transmutation reactor based on a LAR tokamak with an aspect ratio A in the range of 1.5–2.0, which allow a compact sized reactor with a maximum fusion power of 150 MW_{th}, were found following the procedure in Ref. [11]. The plasma physics and engineering constraints of the LAR tokamak were the same as those used in Ref. [10]. With the minor actinides in the blanket, the neutron flux from the fission of the minor actinides will have an impact on the shielding requirements, and the required inboard shield thickness will increase slightly when compared to the case without minor actinides. When considering a fusion power of 150 MW_{th}, shield thicknesses of 40.0 cm for A = 1.5, 44.5 cm for