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Conceptual Study of Transmutation Reactor Based on LAR Tokamak Fusion Neutron Source

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1. Introduction

A compact tokamak reactor concept as a 14 MeV neutron source is desirable from an economic viewpoint for a fusion-driven transmutation reactor. For the optimal design of a reactor, a radial build of reactor components has to be determined by considering the plasma physics and engineering constraints which inter-relate various reactor components. In a transmutation reactor, design of blanket and shield play a key role in determining the size of a reactor; the blanket should produce enough tritium for tritium self-sufficiency, the transmutation rate of waste has to be maximized, and the shield should provide sufficient protection for the superconducting toroidal field (TF) coil. To determine the radial build of the blanket and the shield, not only a radiation transport analysis but also a burn-up calculation were coupled with the system analysis and it allowed the self-consistent determination of the design parameters of a transmutation reactor.

For neutronic optimization of the blanket and the shield, the quantities such as the tritium breeding ratio (TBR), nuclear heating, radiation damage to the toroidal field coil have to be calculated and burn-up rates of Li, actinides and fission products have to be calculated. Thus the neutronic analysis need to be coupled in the system analysis. In most of the previous system studies, neutronic calculation and plasma analysis are performed separately, so blanket and shield size was determined independently from the reactor size. In this work, to account for the interrelation of blanket and shield with the other components of a reactor system, we coupled the system analysis with one-dimensional neutronic calculation to determine the reactor parameters in self-consistent manner.

LAR (Low Aspect Ratio) tokamak plasma has the potential of high β operation with high bootstrap current fractions. In the LAR tokamak reactor, the radial build of TF coil(TFC) and the shield play a key role in determining the size of a reactor since it has impact on the various reactor components. An inboard shield requires improved performance with respect to neutron economy for enough tritium breeding and shielding capability to protect the superconducting TF coil; the fast neutron fluence to the superconductor, the peak nuclear heating in the winding pack, and the radiation dose absorbed by the insulator. In addition to tungsten carbide which has been considered as a shielding material in many reactor studies, metal hydrides such as zirconium hydride and titanium hydride [1,2] are reported to provide a good shielding performance.

Also, to find space for the radiation shielding of the superconducting TF coil inside the torus, high critical current density at high magnetic field strength is required for the TF coil conductor. Recent progress in the development of superconducting material [3], promising much higher engineering critical current density bigger than 10 kA/cm^2 for high magnetic fields, led us to investigate the possibility of employing the superconducting TF coil in the aspect ratios of 1.5 ~ 2.0.

With LAR tokamak reactor as a 14 MeV neutron source, conceptual study of fusion-driven transmutation reactor was performed based on ITER physics and engineering constraints.

2. Tokamak Reactor System Analysis Coupled with Neutronics Analysis

To account for the self-consistent determination of blanket and shield with the other components of a reactor system, we coupled the system analysis [4] with one-dimensional neutronic calculation to determine the reactor parameters in self-consistent manner. One-dimensional radiation transport code, BISON-C [5] with 42 neutron group cross section library based on JENDL-3. For the estimation of the local tritium breeding ratio (TBR), the JENDL dosimetry file is used. BISON-C code consists of two parts. In the first one the one-dimensional transport equation is solved to obtain the neutron and gamma-ray flux. The code employs routines of ANISN [6] - a one-dimensional discrete ordinates code with anisotropic scattering. In the second part the nuclide production- depletion equations are solved for specified time step by Bateman's method using the obtained flux and the burnup library. This library consists of burnup chain data, decay data, and neutron cross sections.

In a system analysis, the main mathematical model to capture the physics and technologies are the plasma power balance equation which is represented as

$$P_{con} + P_{rad} = P_{OH} + P_{\alpha} + P_{CD} \qquad (1)$$

where the conduction (P_{con}) and radiation losses (P_{rad}) are balanced by α particle heating (P_{α}), auxiliary heating (P_{CD}) and ohmic heating (P_{OH}). These terms have a complex dependency on the plasma parameters. For the confinement scaling, the H-mode IPB98y2 scaling law [7,8] is used.

The plasma performance is limited through a beta limit, a plasma current limit imposed by a limitation on the safety factor q at the edge, and the plasma density limit. Appropriate models for plasma composition, non-inductive current drive, bootstrap current fraction, divertor heat load etc. are also needed to calculate plasma performance and for a detailed explanation of these physics constraints, we refer to Ref. [4].

There are various engineering constraints, such as the radial/vertical build, the startup and burn volt-second capability, critical current density in the superconducting coil, the maximum TF field, the stress limit, the ripple condition, the divertor heat load limit and the shield requirements..

3. Minor Actinide Transmutation

By using the coupled analysis system, a LAR tokamak with aspect ratio of 1.8 and fusion power of 150 MW was derived for a neutron source, and the machine parameters are shown in Table 1.

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Table 1 Parameters of a neutron source

Parameters	Value
Fusion power (MW)	150
Major radius (m)	2.8
Minor radius (m)	1.55
Aspect ratio	1.8
Plasma elongation	2.1
Triangularity	0.3
Plasma current (MA)	8.0
Plasma beta	0.125
Edge safety factor	3.5
Neutron wall load (MW/m^2)	0.4
Heating and CD power (MW)	110
H factor	1.4

With minor actinides from PWR spent fuel loaded in outboard blanket, transmutation characteristics are investigated. Table 2 shows the composition of minor actinides in the outboard blanket.

Table 2 Composition of minor actinides in the outboard blanket

Nuclide	Atomic density (10^{-24}/cm^3)
NP236	6.526E^{-09}
NP237	2.786E^{-03}
NP238	6.471E^{-13}
NP239	7.513E^{-10}
NP240	2.098E^{-27}
AM241	4.900E^{-03}
AM243	8.583E^{-04}
CM242	9.103E^{-09}
CM244	5.745E^{-05}
CM245	1.779E^{-05}

Fig. 3 shows variation of k_{eff} and TBR during transmutation operation. By locating the Tritium breeding blanket after the transmutation blanket, Tritium self-sufficiency is easily satisfied due to abundant thermal neutron. The k_{eff} increases initially but decreases as burn-up of minor actinides progress.

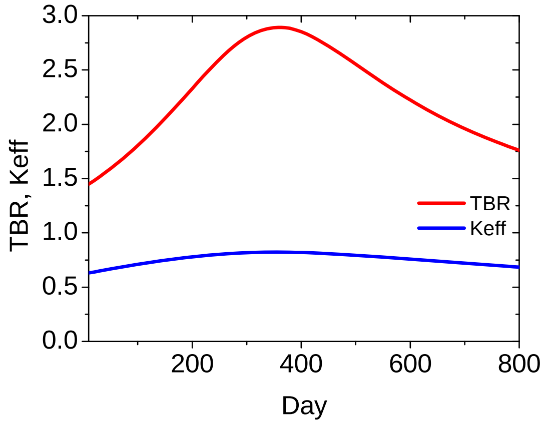

FIG. 1 Variation of k_{eff} and TBR during transmutation operation.

4. Conclusion

For self-consistent calculation of the physical and engineering constraints which relate the various components of a fusion-driven transmutation reactor based on a LAR tokamak concept, the system analysis code was coupled with the one dimensional neutronics code, BISON-C. The coupled system analysis code can provide a comprehensive optimization study of a fusion-driven transmutation reactor with various blanket concepts. It was shown that with the use of advanced technology in the shield and superconducting TF coil, a compact superconducting LAR reactor with aspect ratio of less than 2 can be selected as a 14-MeV neutron source for a fusion-driven transmutation reactor.

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