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Search for reality of solid breeder blanket for DEMO

K. Tobita*, H. Utoh, C. Liu, H. Tanigawa, D. Tsuru, M. Enoeda, T. Yoshida, N. Asakura

Japan Atomic Energy Agency, 801-1 Mukoyama, Naka, Ibaraki 311-0193, Japan

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ABSTRACT

For a tokamak fusion DEMO reactor with the fusion output of 2.95 GW, neutronic and thermal design of blanket is under way to find a feasible blanket concept. For the continuity with the Japanese ITER-TBM options, this study considered water-cooled blanket with solid breeding materials of Li ceramics (Li_4SiO_4, Li_2TiO_3 and Li_2ZrO_3) and Be multipliers (Be and $Be_{12}Ti$). Based on a neutronics-heat coupled analysis, the tritium breeding ratio was evaluated so as to satisfy constraints of the operating temperature of ≤900 °C for Li ceramics and $Be_{12}Ti$, and ≤600 °C for Be. Cooling water condition was assumed to be 23 MPa and 290–360 °C. The result indicates that surplus tritium production in lower neutron wall load (P_n) blanket compensates a shortfall in higher P_n blanket and thus the overall tritium production can marginally satisfy fuel self-sufficiency.

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1. Introduction

Blanket of fusion reactors must satisfies three major requirements: (1) fuel self-sufficiency, (2) removal of heat, and (3) structural strength against thermal stress and electromagnetic forces acting on disruptions. In addition, in a compact high-β reactor, conducting shell structure needs to be installed near the plasma, which can be an additional design requirement to be considered in blanket design. Among the requirements, fuel self-sufficiency is the top priority issue in that external supply of tritium balancing fuel consumption is impossible as a 3 GW plant consumes tritium fuel of about 180 kg every year (=0.5 kg/day × 365 days) Meanwhile, it should be noted that pursuing fuel self-sufficiency conflicts with the other requirements. In this way, a key problem in blanket design is to understand tradeoff issues and to find a reasonable solution meeting all these requirements.

This paper describes a conceptual study on the water-cooled solid breeder blanket of a fusion DEMO reactor, SlimCS. Design philosophy of the blanket is presented in Section 2 from the point of view of system design. Sections 3 and 4 provide descriptions on the blanket concept and its nuclear and thermal characteristics, respectively. Issues for future work are given in Section 5.

2. Design requirements for blanket

2.1. Target of DEMO reactor

The SlimCS fusion DEMO reactor has a major radius of 5.5 m, minor radius (a) of 2.1 m, aspect ratio (A) of 2.6, maximum field of 16.4 T, normalized beta (β_N) of 4.3, fusion output of 2.95 GW, and average neutron wall load of 3 MW/m^2 [1,2]. The reactor is characterized by a reduced-size central solenoid (CS) with an outer radius of 0.7 m, being capable of moderate plasma shaping (triangularity of ∼0.35) and plasma current ramp of 3.8 MA. Although such a CS provides a constraint in tokamak operation, especially in the current ramp-up phase, it has advantages to introduce a thin toroidal coil system, decreasing the reactor weight [3] and perhaps reducing the construction cost. In addition, the reduced-size CS opens a design window in low-A regime, which leads to favorable physical features such as high elongation of plasma, high plasma current, high Greenwald density limit and high beta limit. Main design parameters of the reactor are listed in Table 1.

2.2. Requirements for blanket

From the point of view of system design, requirements for the blanket on SlimCS are summarized as follows:

- TBR––Target of the overall TBR is 1.05. The blanket coverage is 87.2% and the effective coverage of the breeding area, which is defined by eliminating non-breeder zones from the blanket coverage, is 75.9% in SlimCS. In addition, Li burn-up for the solid breeder is estimated to be about 4% for 2-year irradiation at P_n = 3 MW/m^2. As a result, the TBR required for the 1-D model should be 1.43 (=1.05/[0.759 × (1 – 0.04)]) or higher.
- Compatibility with conducting shell––For high β access and vertical stability of plasma, conducting shell structure should be installed near the plasma surface, hopefully r_W/a ≤1.3 where r_W is a distance between the conducting shell and the plasma center.
- Electromagnetic (EM) force conditions––Blanket should be designed to withstand EM forces by disruptions. In our case, the

* Corresponding author. Tel.: +81 292707340.
E-mail address: tobita.kenji30@jaea.go.jp (K. Tobita).

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Table 1
Design parameters of SlimCS.

Major radius, R_p	5.5 m
Minor radius, a	2.1 m
Aspect ratio, A	2.6
Plasma current, I_p	16.7 MA
On-axis magnetic field, B_T	6.0 T
Maximum field, B_{max}	16.4 T
Elongation, κ_{95}	2.0
Plasma volume, V_p	941 m^3
Temperature, T_e	17.0 keV
Density, n_e	1.15×10^{20} m^{-3}
Normalized beta, β_N	4.3
Fusion output, P_{fus}	2.95 GW
Neutron wall load, P_n	~3 MW/m^2

plasma current is assumed to diminish in 0.03 s or longer without suffering a vertical displacement event (VDE). Avoidance of VDE is possible when the plasma position is controlled to be at a neutral point where forces acting on the plasma due to eddy currents are balanced.

- Ease of maintenance––DEMO is required to present a clear vision of efficient maintenance scheme which allows high plant availability toward a commercial plant. A candidate blanket concept needs to be compatible with the maintenance scheme.
- Safety issues––Upon an ingress of coolant event in blanket, a breakage of the blanket casing should be avoided not to contaminate the plasma chamber with water and breeding materials. For this purpose, each blanket may have a decompression mechanism such as a rapture disk which operates immediately after the occurrence of the event [4].

2.3. Materials and water conditions

Temperature range and pressure of cooling water are one of the key design issues. Water temperature is required to be about 300 °C at least so as to avoid corrosion by radiation-produced hydrogen peroxides and radiation embrittlement like light water reactors. However, use in the PWR conditions (15 MPa, 285–325 °C) will not be necessarily feasible in that, when used with such a small temperature difference ΔT (=40 K), the amount of water required to remove nuclear heating can be too large to meet self-sufficient tritium supply. On the other hand, use of supercritical water (25 MPa, 280–510 °C, ΔT = 230 K) [5], which can allow heat removal with a smaller amount of water, is anticipated to lead to serious corrosion of structural material (F82H [6]). With these things considered, we decided to use water in the subcritical water condition of ~23 MPa and 290–360 °C (ΔT = 70 K).

Regarding the blanket cooling channel, a deign target of pressure drop was to be lower than about 0.5 MPa. Water speed and the coolant channel need to be determined to meet these requirements.

3. Conceptual design of blanket

3.1. Torus configuration

Since the first wall area on the outboard side is wide in a low-*A* reactor like SlimCS (inboard 27%, outboard 73%), a demand for tritium breeding on the high field side is comparatively reduced. This leads to a breeding blanket concept consisting of small inboard blanket and large outboard blanket modules. For this reason, SlimCS is designed to have replaceable and permanent blankets on the outboard side while no permanent blanket is installed on the inboard side. In addition, taking account of (1) high availability, (2) compatibility with sector-wide conducting shell and (3) flexible access

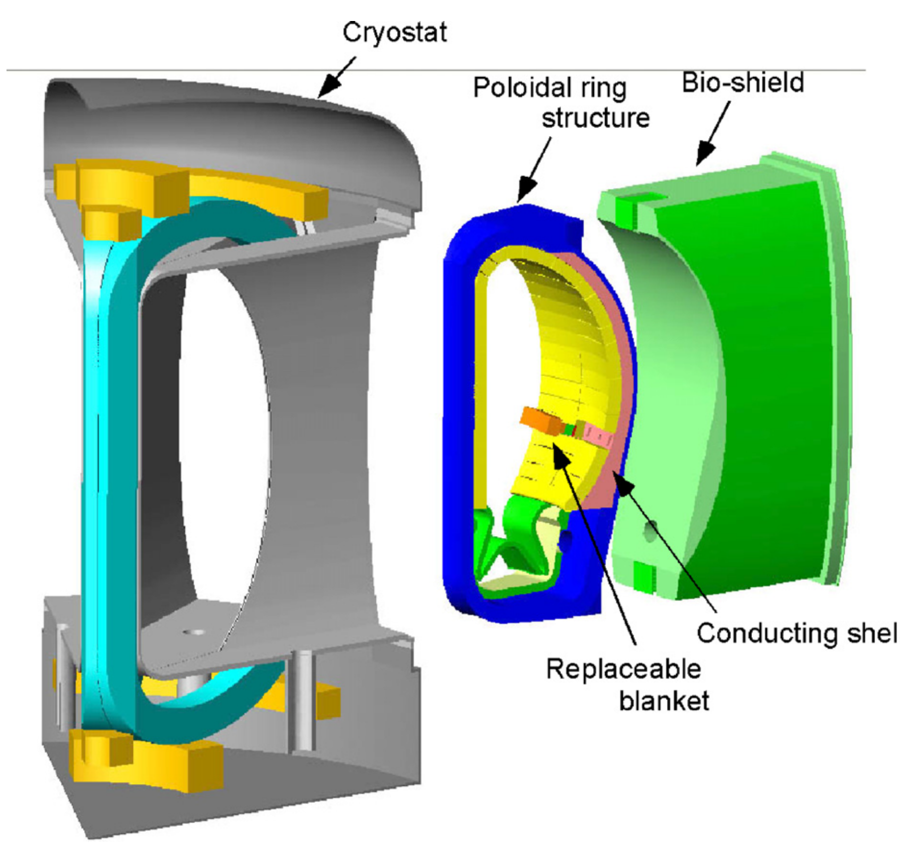

Fig. 1. Torus configuration of SlimCS.

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