ARTICLE IN PRESS

Fusion Engineering and Design xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Assessment of the radioactivity production in water coolant system of WCCB for CFETR

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ARTICLE INFO

Keywords:
CFETR
Water coolant
Water activation products
ACPs

ABSTRACT

A massive amount of radioactive isotopes, including both water activation products and activated corrosion products (ACPs), are produced in the water coolant of a fusion power plant. These are gaining increasing attention, because they determine the occupational radiation exposure during operation and maintenance, and decrease radioactive safety. The purpose of this study is to assess radioactivity production in the coolant system of a water cooled ceramic breeder (WCCB) blanket of the Chinese Fusion Engineering Test Reactor (CFETR) during its design stage. The Monte Carlo N-Particle Transport Code (MCNP) and nuclear inventory code FISPACT-2007 were used to calculate the water activation products, while the CATE 2.1 code was applied to evaluate the ACPs production in the coolant system. In this study, the CFETR was assumed to operate under a 200 MW fusion power with a duty factor of 0.5. Furthermore, the WCCB blanket was assumed to operate for five years (2.5 FPY) prior to dismantling. The specific activity of ^{16}N at the blanket outlet reaches approximately 2.26×10^{12} Bq/kgH_2O, while ^{17}N reaches approximately 6.38×10^{8} Bq/kgH_2O during the operation. The dose rate contributed by water activation products in the coolant system is more than 2.07×10^{3} Sv/h during the operation. At the end of the WCCB operation time, the corrosion products deposited in the pipe surface of the in-flux and out-flux regions are 7.54 and 22.25 kg, respectively, and there are 0.05 g of corrosion products dissolved in the coolant. At the end of the WCCB operation time, the activities at the pipe surface of the in-flux and out-flux regions are 1.78×10^{12} and 4.99×10^{8} Bq/m^2, respectively. Furthermore, the activity contributed by the dissolved ACPs in the coolant is 4.76×10^{4} Bq/kgH_2O during the operation.

1. Introduction

High-energy (14 MeV) neutrons produced by DT fusion reactions, as well as secondary low-energy neutrons produced by neutron interactions with materials in the system, result in various nuclear reactions with reactor materials. Studies on ITER coolant activation reveal that the ^{16}N resulting from the $^{16}O(n,p)^{16}N$ reaction ($T_{\frac{1}{2}}$ = 7.13 s) is the main radioisotope produced by fast neutron reactions in water, and constitutes the dominant source of hard gamma-rays carried by the water flowing out of the blanket, into the cryostat region and beyond [1,2]. Moreover, ^{16}N plays an important role in gamma-ray heating and dose rates from unshielded outlet pipes [1]. Activation corrosion products (ACPs) are also reported to be a major contributor to occupational radiation exposure (ORE) in fusion reactors [3]. Therefore, it is important to evaluate radioactivity production and transportation in the primary heat transfer system (PHTS) as early as possible.

The water cooled ceramic breeder (WCCB) blanket [4], which employs pressurized water as the coolant, is a breeding blanket candidates for CFETR [5], which aims to achieve 200 MW of fusion power and realize 30–50% of the duty time factor. The CFETR WCCB blanket and PHTS are currently in the design stage, and the radioactivity production of the WCCB blanket and PHTS need to be evaluated. Activation analyses of solid materials of the WCCB blanket have previously been addressed in Ref. [6].

In this paper, we present an assessment of radioactivity production in the water coolant of the CFETR WCCB blanket, based on the up-to-date model of the CFETR WCCB blanket. A description of the WCCB blanket and PHTS are provided in Section 2. The models, assumptions, and parameters of the radioactivity calculation are described in Section 3. Finally, the results and a summary are provided in Sections 4 and 5.

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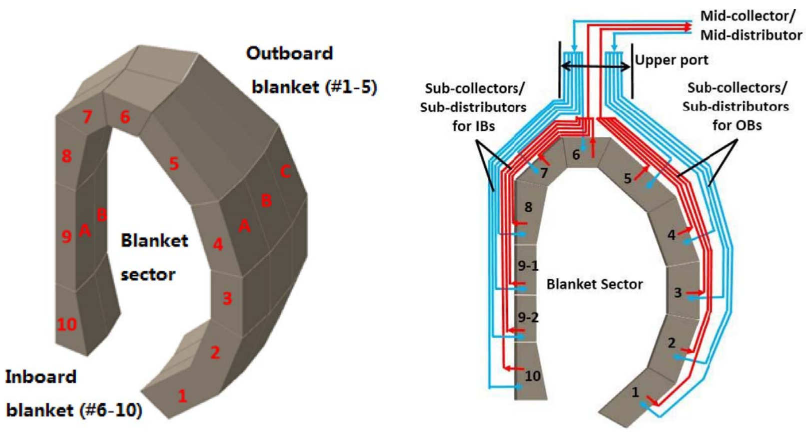
http://dx.doi.org/10.1016/j.fusengdes.2017.09.014
Received 15 February 2017; Received in revised form 27 September 2017; Accepted 27 September 2017



(a) Blanket sector structure (b) Blanket manifold design

Fig. 1. WCCB blanket sector design.

2. WCCB blanket and its PHTS

2.1. WCCB blanket modules design scheme

The CFETR is a 16-sector blanket system, with 22.5° for each sector. Each sector consists of two inboard and three outboard blanket segments along the toroidal direction, as illustrated in Fig. 1(a) [7]. Furthermore, five blanket modules exist in each inboard and outboard segment along the poloidal direction. Blanket module #9 will be split into two identical sub-modules (#9-1 and #9-2, as shown in Fig. 1(b)) with two separate manifolds in order to obtain improved flow distribution [7]. However, blanket modules #9-1 and #9-2 are still regarded as one module in this study, as they share identical parameters.

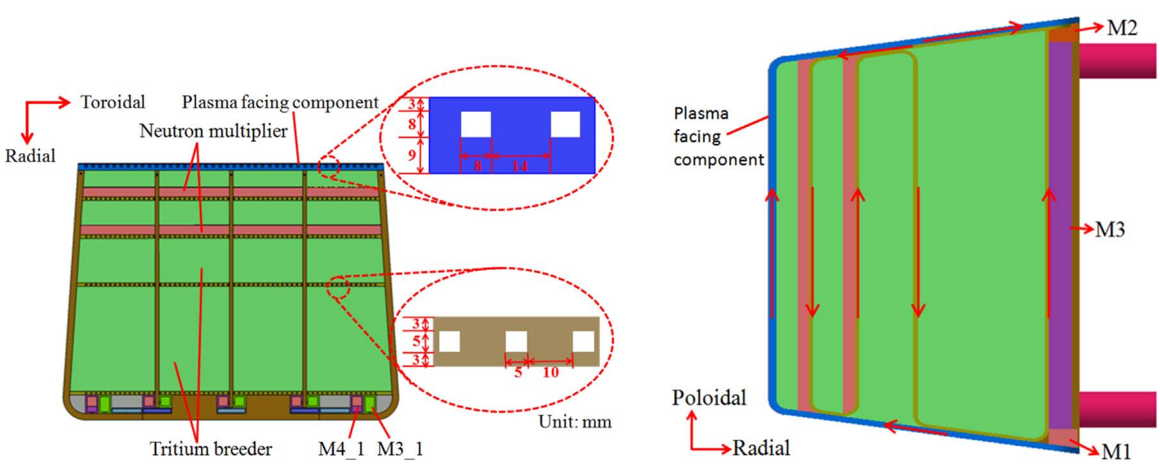
Different modules were designed with different radial arrangements in order to fit the plasma configuration; however, they have similar design features to the structures in [8–10]. The typical structure and arrangement of the blanket modules are depicted in Fig. 2 [8] (using blanket module #3 as an example). Fig. 2a illustrates the radial arrangement of components and distribution of internal channels in the cooling plates. An outboard blanket module contains four cooling plates, while an inboard blanket module includes three cooling plates. The cross-section of an internal channel of the cooling plate is 5 mm × 5 mm, the spacing between two adjacent channels is 14 mm, and the wall thickness of the cooling plate is 3 mm.

The cooling scheme within each blanket module was optimized in addition to the radial arrangement [8]. Fig. 2b displays the cooling scheme: coolant is pumped into the blanket through the first manifold (M1), then distributed into the cooling plates through the second manifold (M2), after which the coolant flows serially in the cooling plates along the radial direction, and is finally collected by M2. Furthermore, the radial stiffening plates are cooled by the coolant distributed and collected by the third manifold (M3). The coolant residence time in each blanket module was estimated to be near 2 s, according to the length of the pipes and velocity of the coolant. A 2-s residence time for the coolant inside the blanket module was applied for water activation analysis in this study, in order to obtain relative conservation results.

The optimized mass flow rates of the coolant in the blanket modules [8] are listed in Table 1.

2.2. WCCB blanket PHTS

Two independent and identical PHTS sets are implemented in the CFETR, and each of these serves eight sections. Each PHTS includes two pumps, one steam generator (SG), one pressurizer, and several pipes and valves, as shown in Fig. 3. The typical lengths of these pipes are also provided in Fig. 3. Water is activated in the blanket modules as there exists a high level of neutron irradiation. In this case, it is assumed



(a) Toroidal cross-section (b) Poloidal cross-section

Fig. 2. WCCB blanket module #3 structure.