Fusion Engineering and Design 146 (2019) 2323–2327

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Assessment of the activation induced by neutron irradiation in K-DEMO and thermal response under the decay heat

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ARTICLE INFO

Keywords:
K-DEMO
Breeding blanket
Divertor
Radioactivity
Decay heat
Thermal analysis
Heat transfer
Cooling

ABSTRACT

The radioactivation of in-vessel components due to the fusion neutrons is an unavoidable trade-off in a tokamak reactor. We investigate the radioactivity level of nuclides and decay heat of conceptual water-cooled ceramic breeder blanket and divertor modules in K-DEMO, and demonstrate that a cooling scheme related to the decay time is important to prevent thermal failure of those components due to decay heat during their maintenance. For K-DEMO with a fusion power of 2.2 GW, the activation levels of blankets and divertors are evaluated regarding a regulatory low level limit in Korea. Total decay heat from radioactivated blankets and divertors reaches 63.4 MW after the full power operation of two years. In an outboard module, immediately after the plasma shutdown, local maximum temperature reaches 1300°C with the temperature difference up to 840 °C inside the module. Conservative natural convection was assumed to validate its integrity to remain within the allowable temperature range of the materials used, when provided that the cool-down time is secured at least a couple of days, the overall temperature of the module is reduced to about 200°C in 10 days. It is worth consideration that a forced convective scheme such an internal passage cooling can be tailored until a critical time corresponding to configurations of each module.

1. Introduction

It is necessary to manage the radioactivity of in-vessel components at a low level and resulting decay heat against their radioactivation due to fusion neutrons although absence of high-level radioactive waste is a great advantage of nuclear fusion power [1–4]. It is foreseen that subsequent decay heat generation from used in-vessel components, such as blankets and divertors, reaches up to tens of megawatt after the plasma shutdown [2,3,5,6]. During the maintenance involving the replacement of in-vessel components, the induced radionuclides, their concentration and decay heat restrict application conditions of remote handling technology. Moreover the induced radioactivation characteristics are critical determinants of disposal methods of the radio-activated components as radiowaste to be [7].

The issue in radioactivation is very important for the design of K-DEMO, particularly for the safety of the reactor [8,9]. A preliminary assessment has to be done to verify whether it can be handled within the scope of intermediate level radioactive waste in accordance with related regulations. The compliance with the regulatory procedures will lead to the optimization of maintenance technologies (*i.e.*, remote handling) [10–12] not only to minimize the amount of radioactive waste but also to maximize the availability of a fusion plant [3,13].

In this study we aim to investigate the radioactive characteristics of a conceptual water-cooled ceramic breeder blanket and a divertor module in K-DEMO. The concentrations of activated nuclides from blankets and divertors are evaluated, and subsequent decay heat is estimated. Accounting for the decay heat analysis, we estimate their thermal response of temperature distributions by 3-D heat transfer analyses using ANSYS Fluent. We demonstrate that cool-down time of components is a key factor in designing a cooling scheme. It is worth consideration that an active cooling, which dissipates heat by a primary heat transfer system passing through the in-vessel components, can be tailored to ensure soundness of the components and optimize a maintenance scenario without their failure.

2. Specification of K-DEMO for the assessment of rad-waste

Fig. 1 shows the schematic of the conceptual K-DEMO tokamak reactor equipped with water-cooled ceramic breeder blankets and divertor modules [14–17]. The tokamak with a fusion power of 2.2 GW is a double null with vertically symmetrical divertors, and has a major radius (R) of 6.8 m and minor radius (a) of 4.2 m [18,19]. A breeding blanket induces sustainable tritium breeding and neutron multiplication through a reaction between neutrons emitted from fusion

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https://doi.org/10.1016/j.fusengdes.2019.03.181
Received 27 September 2018; Received in revised form 26 March 2019; Accepted 27 March 2019
Available online 16 April 2019
0920-3796/

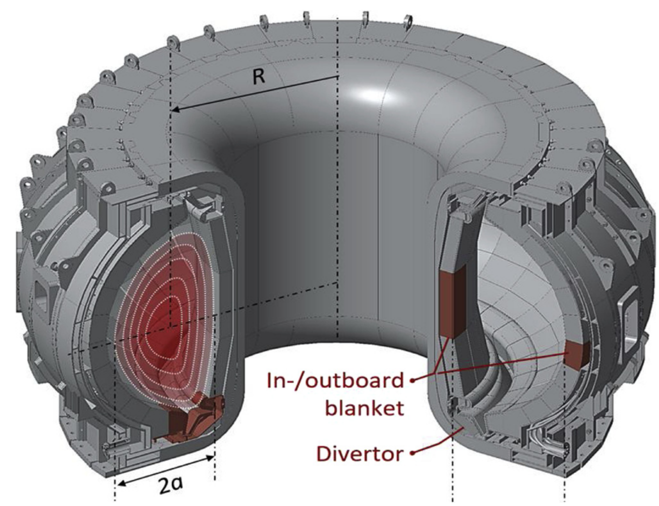

Fig. 1. Schematic of K-DEMO tokamak design [15,18,19].

plasma and materials of breeder and multiplier, respectively. The water-cooled ceramic breeder blanket consists of a plasma facing layer of tungsten, a structural material of reduced activation ferritic martensitic (RAFM) steel and pebble bed layers of Li_4SiO_4 and $Be_{12}Ti$ contained in RAFM steel structures for the respective tritium breeding and neutron multiplication [15,20]. It is a modular component and hundreds of the modules constitute tokamak inner wall [15]. A divertor consists of tungsten mono-blocks, to ensure mechanical robustness against high heat flux, RAFM steel heat sinks and a cassette body with internal

cooling passages [20–22]. In both models, internal cooling passages are shaped for a pressurized water coolant [15,17,21,23]. Table 1 presents the weight of conceptual modules of K-DEMO blanket and divertor components discharged at every replacements.

3. Assessment of radioactivation of in-vessel components

The neutron wall load (NWL) applied to plasma facing surfaces is calculated for the fusion power of 2.2 GW. Local NWL on the first wall (FW) is estimated using a developed in-house code [24]. When the geometric information is set first, the plasma region, where is for the plasma core and the scrape-off layer (SOL), and the FW are to be segmented. Then it calculates the quantity of the neutron load distribution from each source (*i.e.*, plasma radiation and neutron) point to each target segment on FW considering the solid angles. Fig. 2 shows NWL applied to the in-vessel components in the poloidal direction. An average NWL applied to the FW of the in-vessel components exceeds 1 MW/m^2, and FW of an equatorial outboard blanket is exposed to 2.83 MW/m^2. Accounting for this profile, we analyze the radioactivation level and decay heat generation of the water-cooled ceramic breeder blanket and divertor by an in-house code utilizing a nuclide emission data library [25,26]. In the calculation process using this code, it is assumed that the in-vessel components are exposed to the fusion neutrons irradiated from the reactor for 2 years. In addition the blanket and the divertor components are handled as 1-D layered models as

Table 1
Weight of in-vessel components.

Components	Layer	Weight [ton]
Blanket	W	49.42
	RAFM	526.7
	Pebbles	335.4
Divertor	W	120.0
	RAFM	1211

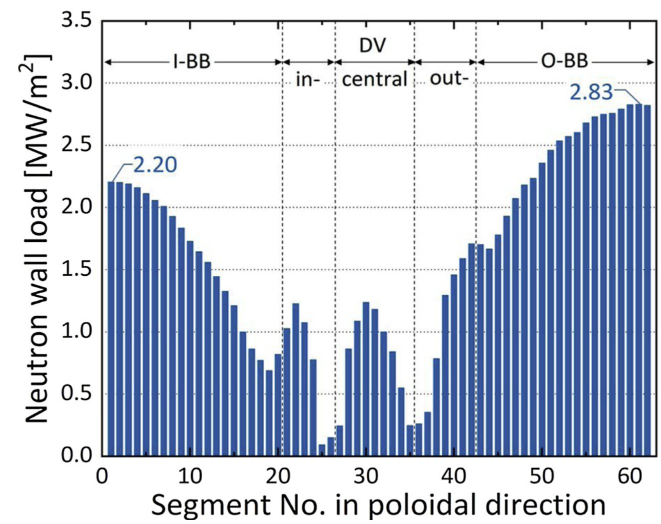

Fig. 2. Neutron wall loading profile on the in- and outboard blanket (I-BB and O-BB) and divertor (DV).

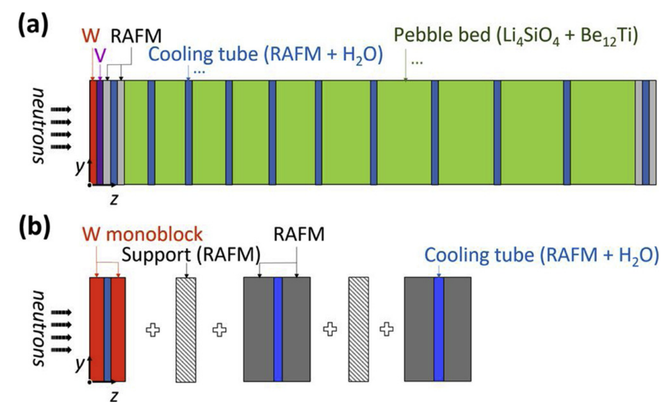

Fig. 3. Schematic of in-vessel components of breeding blanket and divertor module. 1-dimensional structure of (a) the water-cooled ceramic breeder blanket and (b) divertor module for radioactive characteristics analysis [5,6].

schematically presented in Fig. 3. In a blanket model a plasma facing W layer, an adhesion layer of vanadium, RAFM steel structures and the pebble beds are represented by a series of layer structures. The 1-D divertor model describes tungsten mono-blocks, heat sinks made of RAFM steel and a cassette body. Through

the neutron transport analysis using a Monte Carlo neutron particle transport code (MCNP), the neutron flux is derived to each layer in the 1-D model according to refined energy levels from 10^{-10} to 14.1 MeV [20]. Then the degree of neutron flux attenuation along the depth of the modules is correlated as a function of position, and extrapolated on every surfaces and cells constituting the model in terms of configurations (*i.e.*, shapes and materials) of each blanket and divertor. The radioactivity and consequent decay heat characteristics are then quantitatively derived as a function of time and position of each constituent element of the structure [20]. Accounting for the decay heat after plasma shutdown, the consequent thermal behaviors of the components are characterized by 3-D heat transfer analyses using an ANSYS Fluent (v18.0) software under quasi-steady state conditions according to the time increase.

4. Radioactivity and classification of the waste

Fig. 4 shows the time-dependent radioactivity originated from the blanket and divertor mounted in the tokamak. The plasma facing tungsten layer shows a high activation in both blanket and divertor. It

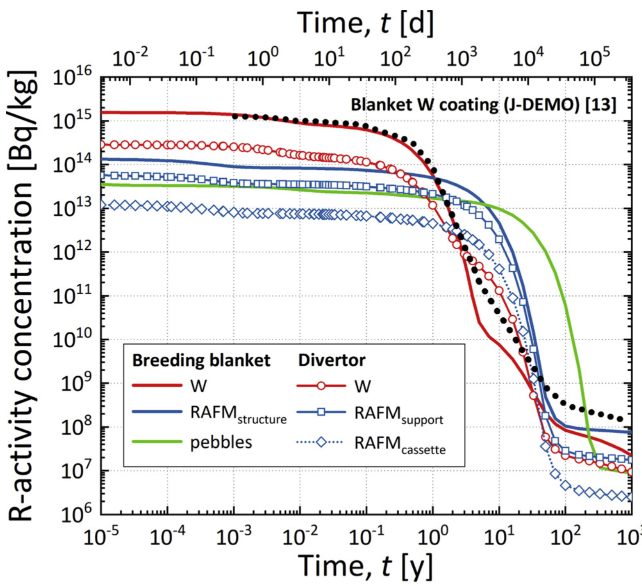

Fig. 4. Radioactivity concentrations on the breeding blanket and the divertor under 2.2 GW fusion power of K-DEMO. A dotted blank line indicates the comparison result on a tungsten coating layer of a breeding blanket in a reference of Japanese DEMO study [13].

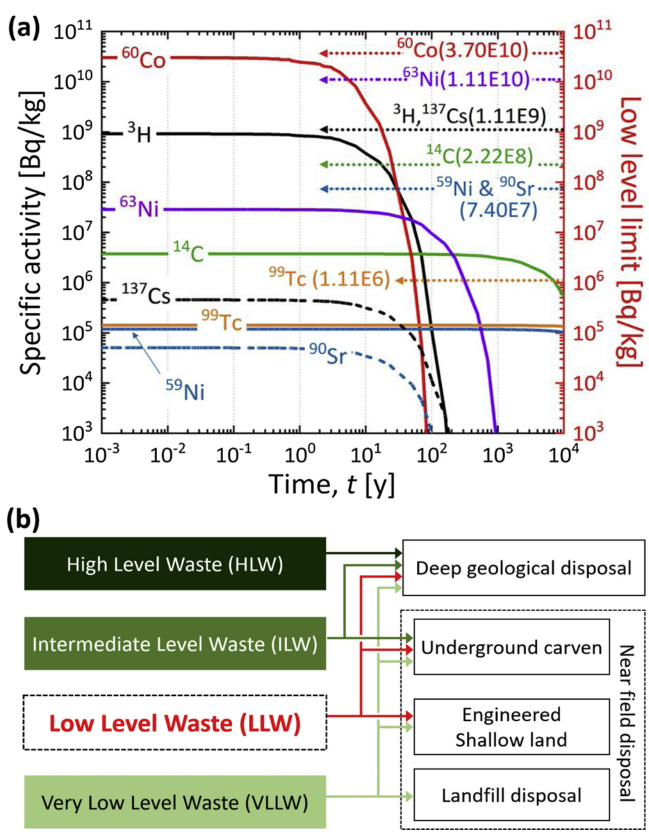

Fig. 5. (a) Radioactivity and low level boundaries of nuclides from the tungsten first wall in outboard breeding blanket. (b) Classification of radioactive waste and resultant disposal methods based on a Korean regulation [27–29].

can be stated the cooling time after plasma shutdown is a deterministic factor of their radioactivity and a design parameter of maintenance [13]. The activation levels of W in the blanket and divertor decrease in time and become 3.16% and 3.50% in a year compared to their initial values, respectively. Fig. 5a shows activated nuclides from the tungsten FW located in an equatorial outboard blanket where the highest radioactivation is predicted with NWL of 2.83 MW/m^2. In the graph, baselines which specifies low level limit of rad-wastes in Korea are also indicated [27]. Fig. 5(b) explains the classification of rad-waste and corresponding disposal methods in Korea [13,27–29]. The rad-waste should be handled in accordance with the regulation and be indicated into the low level waste, which can be disposed of in shallow land burial in the light of social and economic susceptibility of a fusion plant. Considering the baselines, we confirm that long-half-life radionuclides such as ^{14}C ($t_{1/2}$ = 5700 y), ^{60}Co ($t_{1/2}$ = 5.27 y) and ^{99}Tc ($t_{1/2}$ = 2.1 × 10^5 y) can be kept below their specific baseline activity of 3.74 × 10^6, 3.02 × 10^{10} and 1.41 × 10^5 Bq/kg, respectively. The results demonstrate those noxious nuclides remains below the low level limit. The replacement of the components and disposal must be performed depending on the level of activity concentrations [26]. In other words, the legitimate classification as shown in Fig. 5b will be a guideline for designing a maintenance period and a consequential disposal method regarding the activation.

5. Assessment of decay heat for cooling design

For thermal analyses, a commercial computational fluid dynamic code of ANSYS Fluent (v18.0) was used as a solver. For the blanket and divertor modules, 3-dimensional temperature on both blanket and divertor modules was evaluated under a quasi-steady state condition. Particularly on blanket models, preliminary mesh dependence were checked, and structured meshes more than 1.9 million were used with at least 7 layers in the thinnest structure. Natural convection excluding other cooling schemes is assumed on the outmost surface of a target module with heat transfer coefficient of 10 W/m^{2}K for conservative assessment of thermal reliability.

Fig. 6 shows the variation of decay heat from the in-vessel components. Immediately after the plasma shutdown, the in- and outboard blanket and the divertor generate decay heat by 13.0, 42.1 and 8.34 MW, respectively. Total decay heat drastically decreases from 63.4 (at t = 0 s) to 7.44 (11.0%), 3.16 (4.97%), 2.82 (4.44%) and 2.55 MW (4.02%) as t increases to 1, 7, 15 and 30 days, respectively. Consequent local temperature is also evaluated to validate whether it would be secured below their melting points. In case of a divertor (Fig. 7(a)), the maximum temperature of a divertor readily decreases with time; a separate divertor shows the highest temperature of 418.3, 336.6 and

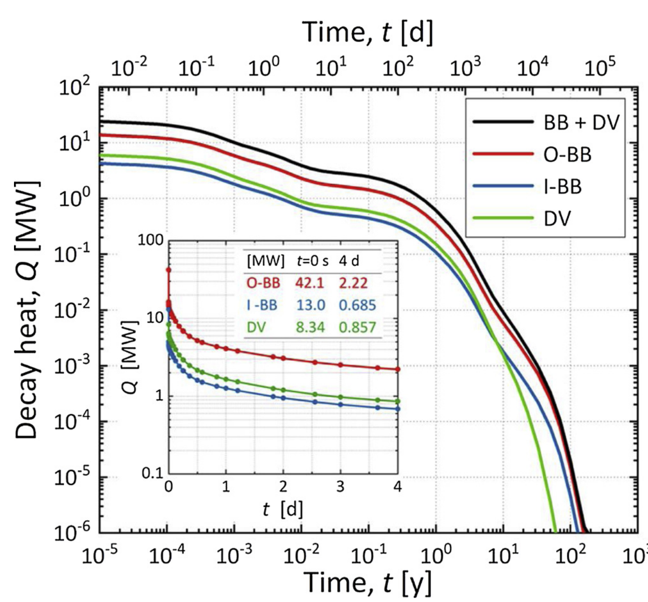

Fig. 6. Decay heat of the components after the plasma shutdown. O-BB, I-BB and DV indicate the outboard breeding blanket, the inboard breeding blanket and the divertor, respectively.

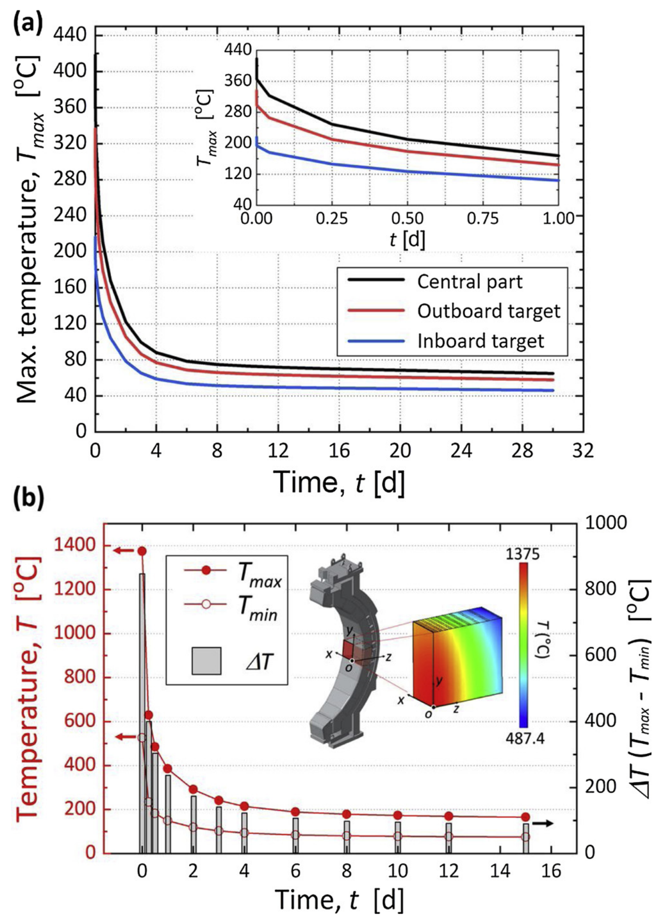

Fig. 7. (a) Local maximum temperature of a divertor module. (b) Local temperature of an outboard blanket located at equatorial port. The red-colored lines with solid and blank circles are the local maximum and the minimum temperature in the blanket, respectively. The black-colored bar graphs is the temperature difference in the blanket. Inset shows temperature contours in the blanket module just after the plasma shutdown (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

216.3 °C in central-,

outboard- and inboard target, respectively. For the central part it takes at least 3 days while overall temperature falls below 100 °C. In an outboard blanket module (Fig. 7(b)), decay heat leads to local temperature increase over 1300 °C and spatial temperature difference of 840 °C within a module. Otherwise, the natural convection without any forced convective cooling can be valid only after the specific cool-down period of at least a couple of days; local maximum temperature in the blanket decreases to 220 °C and 180 °C with the time of 4 and 10 days, respectively. These results demonstrate the cool-down time is important in designing a maintenance scheme. Particularly in the specific period with high decay heat, the significant temperature difference might lead to unexpected failure due to consequent thermal stresses. In this regard, an appropriate cooling scheme involving an active cooling through internal passages of in-vessel components should be employed considering the transient thermal behaviors, which depend on configurations of each component.

It is important that each component should be as intact as possible, and related facilities be prevented from being damaged due to thermal failure induced by decay heat. In order to minimize the volume of radioactive waste, an optimal maintenance scheme should be devised through the reuse or recycling of materials used for the in-vessel components. Furthermore, the decay heat should be regarded as a primary source term deteriorating the safety of a DEMO system [8,30,31]. The conservative assessment on safety issues, assuming the worst accidents, and sequential feedback on design will be the basis of our future studies for the design of a reliable fusion plant.

6. Conclusion

The radioactivation of in-vessel components is inevitable in a fusion tokamak reactor. In a design phase of a DEMO, the concentration of radioactive nuclides and decay heat should be treated as factors determining a replacement and subsequent disposal strategy of in-vessel components. In this study we investigated the activation levels of water-cooled ceramic breeder blankets and divertors in K-DEMO in respect to a regulatory low level limit in Korea. We assessed decay heat generation; total decay heat from the in-vessel components reaches up to 63.4 MW after two years of the full power operation of a conceptual K-DEMO with the target fusion power of 2.2 GW. It is worth consideration that alternative cooling schemes involving an active cooling can be tailored at the time when excessive decay heat occurs. The activation characteristics will be further assessed for the global K-DEMO model, and will be discussed to clarify design parameters of hot cell and related maintenance scenarios [12]. The integrated decay heat results will also be employed as prerequisites of a transient thermo-hydraulic analysis for safety assessment of K-DEMO.

Acknowledgements

This research was supported by R&D Program of "Study of Demonstration Plant Design Concept and Base Technology (CN1801)" through the National Fusion Research Institute of Korea (NFRI) funded by the Government funds.

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