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Activation calculation and radiation analysis for China Fusion Engineering Test Reactor

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HIGHLIGHTS

- Activation calculation was performed using FLUKA for the main components of CFETR.
- Radionuclides and radioactive wastes were assessed for CFETR.
- The Waste Disposal Ratings (WDR) were assessed for CFETR.

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ABSTRACT

The activation calculation and analysis for the China Fusion Engineering Test Reactor (CFETR) will play an important role in its system design, maintenance, inspection and assessment of nuclear waste. Using the multi-particle transport code FLUKA and its associated data library, we calculated the radioactivity, specific activity, waste disposal rating from activation products, nuclides in the tritium breeding blanket, shielding layer, vacuum vessel and toroidal field coil (TFC) of CFETR. This paper presents the calculation results including neutron flux, activation products and waste disposal rating after one-year full operation of the CFETR. The findings show that, under the assumption of one-year operation at the 200 MW fusion power, the total radioactivity inventory will be 1.05×10^{19} Bq at shutdown and 1.03×10^{17} Bq after ten years. The primary residual nuclide is found to be ^{55}Fe in ten years after the shutdown. The waste disposal rating (WDR) values are very low («1), according to Class C limits, CFETR materials are qualified for shallow land burial. It is shown that CFETR has no serious activation safety issue.

1. Introduction

The China Fusion Engineering Test Reactor (CFETR) is a new superconducting magnet tokamak device being designed by the China National Integration Design Group for Magnetic Confinement Fusion [1,2]. The design considers three breeding blanket concepts including helium-cooled solid blanket, water-cooled solid blanket and liquid metal-cooled liquid blanket. Among the three option, the helium-cooled solid blanket concept is the first and most detailed design for CFETR due to the fact that the China Helium-cooled Solid Breeder (CH HCSB) test blanket module (TBM) will be tested in ITER facility. So the helium-cooled solid blanket concept is used for analysis in this paper. Its scale and structures are similar to those of the ITER device. It is composed of the following main components: vacuum vessel, inner thermal shield, toroidal field coils (TFC), central solenoid coils (CSC), poloidal field coils (PFC), outer thermal shield and cryostat. The overview structure of CFETR is shown in Fig. 1 [3]. The objectives of the design are to achieve long pulse or steady-state operation with the duty cycle time $\geq$0.3 ~ 0.5, to demonstrate the generation of fusion power and to realize tritium self-sufficiency with installing suitable breeding blankets.

Prediction of all activation sources and their potential hazard in CFETR is essential for the purposes of selecting blanket and shield material, analyzing the safety and environment, disposing nuclear waste and operating the reactor. In this study, we used multi-particle Monte Carlo transport code, FLUKA, and its associated data library [4,5] to calculate the radioactivity, specific activity, and waste disposal rating from activation products, nuclides in the tritium breeding blanket, shielding layer, vacuum vessel and TFC of CFETR. These results are expected to provide reference data for designing the CFETR components and its further neutron activation analysis.

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Table 1
One dimensional geometry model for CFETR.

Regions	*R*/cm	Δ*R*/cm	Material layout
1. First wall	1.4	1.4	Water vapor (41.558%) + RAFM (58.442%)
2. Breeding material	1.9	0.5	Li_4SiO_4 (88%) + RAFM (12%)
3. Structure material	2.8	0.9	Water vapor (39.68%) + RAFM (60.32%)
4. Neutron multiplication material	7.8	5.0	Be (88%) + RAFM (12%)
5. Structure material	8.7	0.9	Liquid water (39.68%) + RAFM (60.32%)
6. Breeding material	9.7	1.0	Li_4SiO_4 (88%) + RAFM (2%)
7. Structure material	10.6	0.9	Liquid water (39.68%) + RAFM (60.32%)
8. Neutron multiplication material	16.6	6.0	Be (88%) + RAFM (12%)
9. Structure material	17.5	0.9	Liquid water (39.68%) + RAFM (60.32%)
10. Breeding material	18.5	1.0	Li_4SiO_4 (88%) + RAFM (12%)
11. Structure material	19.4	0.9	Liquid water (39.68%) + RAFM (60.32%)
12. Neutron multiplication material	26.4	7.0	Be (88%) + RAFM (12%)
13. Structure material	27.3	0.9	Liquid water (39.68%) + RAFM (60.32%)
14. Breeding material	28.3	1.0	Li_4SiO_4 (88%) + RAFM (12%)
15. Structure material	29.2	0.9	Liquid water (37.24%) + RAFM (62.76%)
16. Neutron multiplication material	35.2	6.0	Be (88%) + RAFM (12%)
17. Structure material	36.1	0.9	Liquid water (37.24%) + RAFM (62.76%)
18. Breeding material	38.1	2.0	Li_4SiO_4 (88%) + RAFM (12%)
19. Structure material	39.0	0.9	Liquid water (37.24%) + RAFM (62.76%)
20. Vessel Vacuum	40.0	1.0	Void
21. Shielding	83.0	43.0	316 Steel (60%) + liquid water(40%)
22. Vessel Vacuum	86.0	3.0	Void
23. VV structure material	114.0	28.0	VV mixed material
24. Vessel Vacuum	126.0	12.0	void
25. TFC surface	136.0	10.0	316 Steel
26. TFC insulating layer	137.2	1.2	Epoxy insulation material
27. TFC magnet	202.2	65.0	Nb_3Sn
28. TFC insulating layer	203.4	1.2	Epoxy insulation material
29. TFC surface	213.4	10.0	316 Steel

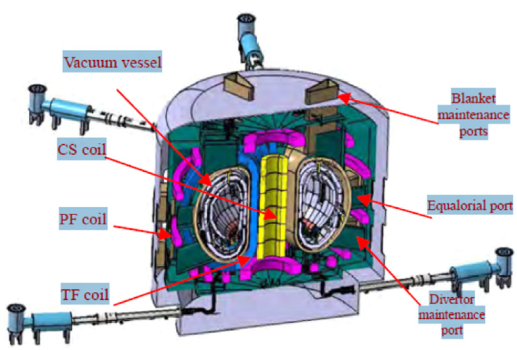

Fig. 1. The overview conceptual structure of the CFETR tokamak machine.

2. Models and tools

The FLUKA code was chosen to calculate radioactivity for CFETR. As an open and free code, FLUKA is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of nuclear engineering and medical physics applications. For neutrons less than 20 MeV, FLUKA has its own neutron cross section database which includes more than 250 nuclides (Scattering angular distribution with P5 Legendre angle expansion, 260 neutron energy groups). In FLUKA, its library is continuously enriched and updated on the basis of the most recent evaluations (ENDF/B, JEFF, JENDL etc.). The library format is similar to that known as ANISN (or FIDO) format. FULKA uses multigroup libraries and corrections for the "self-shielding" effects have been included in the FLUKA libraries for important elements [6]. In our previous studies, we compared the results from FLUKA with those by other codes and the potential errors were within 15% of the error [7–10].

Activation calculation was performed assuming a continuous irradiation over one year at full fusion power (200 MW). The thickness of the blanket needed for tritium breeding and shielding is estimated to be 1 m in the inboard blanket direction and 1.2 m in outboard blanket direction. A neutron wall loading in the range of 1.5–3 MW/m^2 is proposed for the design of CFETR [11–15]. In neutronics transport calculation, neutron wall loading is set to 1.5 MW/m^2 on the First Wall (FW).

Taking one set of primary parameters of CFETR in reference [15], the major and minor radii are assumed to be 5.5 m and 1.5 m, respectively. As CFETR is in the early concept design step, a one-dimension (1D) model was used in this study for simplicity. Table 1 summaries the 1D geometric model schematic and materials used in the calculation, where "R" represents the distance from the plasma edge and "ΔR" represents the thickness of related region. Material selection for blanket safety is carefully evaluated in this study [16]. The design considers the Reduced Activation Ferritic/Martensitic (RAFM) steel [17] as the structure material, Li_4SiO_4 pebbles as the breeder materials, and beryllium pebble as the neutron multiplier. The activation behaviors of these materials are affected to a great extent by impurities or impurity elements; their transmutation dominates the level of activation for a long time after shutdown. For the activation calculations, it is therefore mandatory to take into account of tramp elements and impurities of the materials being considered in the design. Table 2 describes the basic impurities considered in the neutron multiplier (Be), structure material and tritium breeder (Li_4SiO_4). According to CFETR's mission, its full power operation time is only one year, so the irradiation scenario in this study is assumed to be one year [2].

3. Results and analysis

3.1. Neutron flux

Under the high-energy neutron field, the neutron multiplier, structure materials and tritium breeder have significant activation reactions, leading to many radioactive materials. The radioactivity calculation depends largely on the neutron flux. Fig. 2 shows that the fast neutron (>0.1 MeV) flux density radial profile in the outboard blanket ~1.2 m in thickness, which is normalized to the neutron wall loading ~1.5 MW/m^2. The statistical errors of the

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