Fusion Engineering and Design 159 (2020) 111751

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Operation and shutdown dose rate analysis of CFETR ECRH system

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ARTICLE INFO

Keywords:
CFETR
ECRH
Operation dose
Shutdown dose
NASCA

ABSTRACT

Electron Cyclotron Resonance Heating (ECRH) is one of auxiliary heating systems to be installed in CFETR. For heating purpose of ECRH, a penetration space has been designed to transmit the wave to plasma. This will significantly increase the neutrons streaming through the wave channel and result in heavy irradiation of ECRH port structures. For nuclear safety analysis, the irradiation dose during operation of CFETR should be limited according to the regulation of radiological zone. In case of failure, the ECRH is planned to be maintained by workers after shutdown and waiting time of one month until the dose rate decreases to low level of 100 μSv/h. The shielding capabilities of ECRH port has been evaluated in view of dose effect both during operation and after shutdown of CFETR. For that purpose, a 3-D neutronics model has been built to launch the nuclear analysis. The operation dose rate was directly transferred from the neutron and photon flux by using of ICRP-74 flux to dose conversion factors. The shutdown dose rate was obtained with NASCA code system by coupling the Monte Carlo particle transport and FISPACT activation calculation. The obtained operation and shutdown dose data can be provided for the shielding optimization of ECRH wave system.

1. Introduction

China Fusion Engineering Test Reactor (CFETR) (Fig. 1) is planned to heat and stabilize the plasma in support of auxiliary systems including electron cyclotron resonance heating (ECRH), ion cyclotron resonance heating (ICRH), low hybrid wave (LHW) and neutral beam injection (NBI) [2]. ECRH is designed to transmit the power of 30 MW at 170 GHz to plasma [3]. Three upper ports are to be used to install the ECRH wave system. At port space, the ECRH includes waveguides to transmit the wave, mirrors to focus and inject the wave in order to heat the plasma at different angles. For heating purpose, a penetration structure is designed to connecting the blanket and waveguides in order to transmit wave to plasma. This will significantly increase the neutrons streaming through the channel and result in heavy irradiation of ECRH port structures. The ECRH design has considered strict neutron shielding and some shielding structures have been added around the port.

The shielding design should meet requirement of low dose rate level to guarantee the safety of workers in radiological zone like building above ECRH port. And the working time in such building should also be limited. The identification of radiological zone for a fusion reactor in China has not been issued so far. While some proposals have been made for CFETR radiological zone referring to the ITER regulation and limited by Chinese domestic regulations linking to the fission reactors like PWR (NB/T 20185-2012) [4,5]. The proposal suggests that the CFETR radiological zone contains supervised zone and controlled zone. In the supervised zone, which is colored by blue (Table 1), the dose rate should be less than 2.5 μSv/h and the working time should be less than 2000 h per year. The dose rate limit and access conditions of radiological zone can be seen in Table 1.

In case of failure, the ECRH is planned to be maintained by workers after shutdown and waiting time of one month until the dose rate decreases to low level of 100 μSv/h. In this paper, the detailed neutronics model, computational methods and results are presented. The operation and shutdown dose rate are analyzed to evaluate the shielding capabilities of ECRH wave system.

2. Engineering and neutronics model

ECRH wave system at port zone consists of waveguides and mirrors,

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https://doi.org/10.1016/j.fusengdes.2020.111751
Received 31 December 2019; Received in revised form 17 April 2020; Accepted 10 May 2020
Available online 30 May 2020
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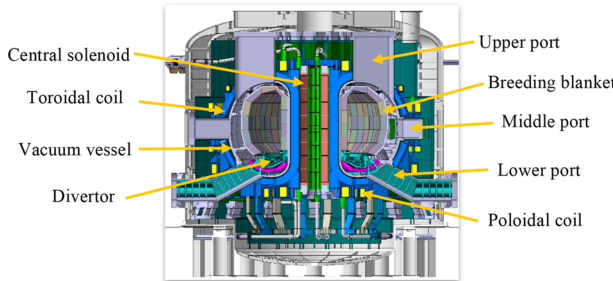

Fig. 1. Sketch of the CFETR [1].

shown in Fig. 2. There are 8 small focus mirrors in array. For neutronics calculation, it has been simplified to be a single mirror, 450 × 850 mm in size. There are two injection mirrors with a size of 550 × 750 mm. The neutronics model for ECRH dose rate analysis is shown in Fig. 3. The ECRH neutronics model was built in the support of McCad conversion tool. McCad is developed by KIT/INR as visualization interface and automatical conversion software [6]. The model contains the CFETR main machine, the ECRH waveguides and port, and the concrete building outside the main machine. The water cooled ceramic breeder (WCCB) blanket with full detailed structure was introduced into this model [7]. The neutron shielding performance of WCCB has been evaluated and it meets the nuclear responses limit required from engineering design of VV and toroidal field coils (TFC) [8]. In order to transmit the wave to plasma, a penetration space is designed by replacing the blanket and the size of cross section is about 1 m^2. The shielding has been added around the penetration space to stop the neutrons streaming through the port to decrease irradiation damage to VV and TF coils. The cross section of ECRH port can be seen in Fig. 3 (upper right) and the blanket opening in Fig. 3 (bottom right). The shielding capacities and neutron damage effect meet the requirement of VV and TFC design after neutronics analysis and such results will be published later [9].

At ECRH port, the space has been divided into three zones (A, B and C) seperated by support structures. At position C it is planned to maintain the ECRH system by workers after reactor shutdown. Thus dose rate at position C should be limited below 100 μSv/h 1 month after shutdown. While at position A and B it is predictable that the dose rate is above the limit to allow access by workers.

The material specification of ECRH can be seen in Table 2. The material of waveguide is SS316LN steel, mirror is oxygen free copper (OFC) and the support is mixture of 80% CLAM steel and 20% water. The low activated RAFM steel CLAM has been considered here mainly

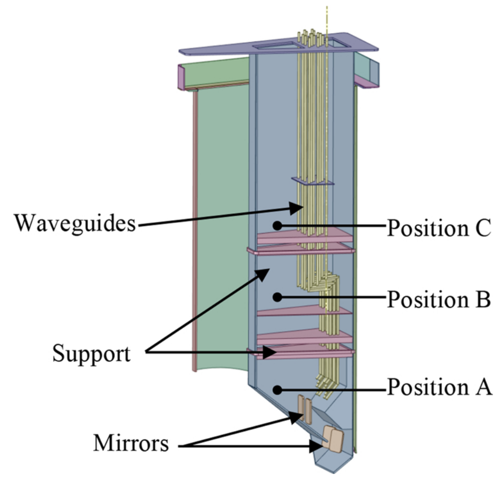

Fig. 2. The neutronics model of CFETR with building (left), the detailed ECRH port structure (upper right) and cross section of opening blanket (bottom right).

to reduce the activation level in case of entering of workers for maintenance. The bio-shielding is 2.5 m wide in the vertical direction. At upper port, the bio-shielding is 1.5 m wide in the horizontal direction. The design of bio-shielding should guarantee adequate neutron shielding capabilities. Detail analysis is shown below.

3. Methodologies

The particle transport was performed by using of MCNP5 code combined with FENDL-2.1 nuclear data library [10,11]. The advanced 'on-the-fly' global variance reduction (GVR) technology has been used to generate the global map of weight window to accelerate the particle transport. 'On-the-fly' method is a global variance reduction technology developed with cooperation of ASIPP and KIT [12]. This method only initials the neutron flux as weight window for next iterated particle transport. On the other hand, the 'long-history' problem has also been alleviated. 'on-the-fly' GVR has been validated on the ITER calculation and the speedup factor is about 72 compared to the analog computation [12]. This method has been used here for CFETR ECRH port neutronics calculation.

For operation dose rate calculation, the dose was directly transferred from the neutron and photon flux by using of ICRP-74 flux to dose conversion factors. The shutdown dose rate was calculated by using of NASCA code to coupling the MCNP particle transport and FISPACT nuclides inventory calculation [13,14]. To use the NASCA for

Table 1
Proposed radiological zone identification of CFETR.

			Dose rate	Access conditions
Radiological working zone	Supervised zone	Blue zone	≤ 2.5 μSv/h	Working time less than 2000 h per year
	Controlled zone	Green zone	≤ 10 μSv/h	Normal access, working time less than 2000 h per year
		Yellow zone	≤ 1 mSv/h	Limited access
		Orange zone	≤ 10 mSv/h	Limited access
		Red zone	≥ 10 mSv/h	Prohibited access

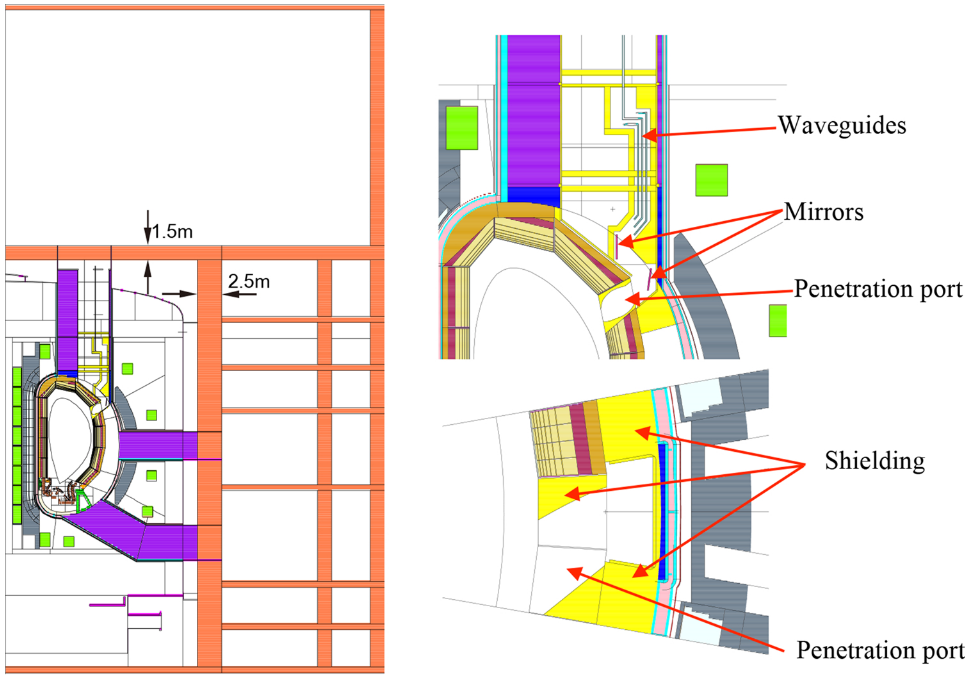

Fig. 3. ECRH waveguide system inside port and the shielding design.

Table 2
Material specification of ECRH waveguide system.

Components	Material
Waveguide	SS316LN
Mirror	Oxygen free copper (OFC)
Support	80% CLAM steel + 20% water

shutdown dose rate calculation, the factors related the mono-energetic neutron flux to decay gamma intensity for every defined material and every cooling step have been calculated in advance. Then these factors have been used to decide the particle characteristics such as energy and weight of emitted decay gammas produced by neutron colliding. Thus the coupled neutron and decay gamma transport can be achieved in one MCNP run for fast calculation of shutdown dose rate. The NASCA method is able to calculate the shutdown dose rate for several cooling steps simultaneously in one MCNP run. Here at cooling time of 1, 3, 7, 12, 15, 20, 25 and 30 days the dose rate have been calculated only once in MCNP.

4. Operation dose rate

The neutron and photon transport was launched to get the flux distribution and the dose of total neutron and photon can be transferred by using of flux to dose conversion factors. The neutron flux distribution and statistic relative error can be seen in Fig. 4. The statistic relative error is below 5% at most area when 'on-the-fly' GVR is introduced to accelerate the Monte Carlo particle transport. It satisfies the requirement of nuclear analysis.

The operation dose rate map of CFETR is shown in Fig. 5. The fusion power of CFETR is assumed 1.5 GW as severest neutron irradiation situation. During operation of CFETR, the area inside the bio-shielding is forbidden for human's access as the dose is too high as more than 50–300 Sv/h inside the cryostat. At ECRH port, the dose rate at bottom of port is extremely high due to the blanket opening as about 10^5 Sv/h. The dose rate varies from top to bottom of the port at range of 0.1 to 10^5 Sv/h, shown in Fig. 6. Due to the shielding of support structure, the dose rate in the middle interspace decrease to 0.1 Sv/h. At top of port, the dose rate slightly increases to about 10 Sv/h due to the weak shielding of port outside the cryostat. This will be checked with engineering design group and additional shields are proposed to be added at top of port.

Due to the blanket opening, the area outside the opening and inside the cryostat is obviously higher, approximately 300 Sv/h, than other areas. For example, in the middle and inside the cryostat it is about 50 Sv/h. At the area below the divertor, the dose rate is slightly higher, about 100 Sv/h, due to neutron leakage from the divertor.

At outboard blanket close to plasma, the dose rate is about 10^8 Sv/h. The dose rate inside and close to bio-shielding is about 1 Sv/h. It decreases rapidly through the bio-shielding. Fig. 7 shows dose rate from outboard blanket to building in equatorial plane. In most locations in the building the dose rate is extremely low, even less than 0.1 μSv/h which is lower than natural background level. Only at top area of building, the dose rate is about 100 μSv/h. According to the identification of CFETR radiological zone, it's yellow zone and it should be limited for access of workers. While in practice, the neutron streaming of gaps, pipes or other penetrations in detailed structure has not been evaluated in this calculation. The access of these area should be re-evaluated after the detail design of penetrations and other structures.

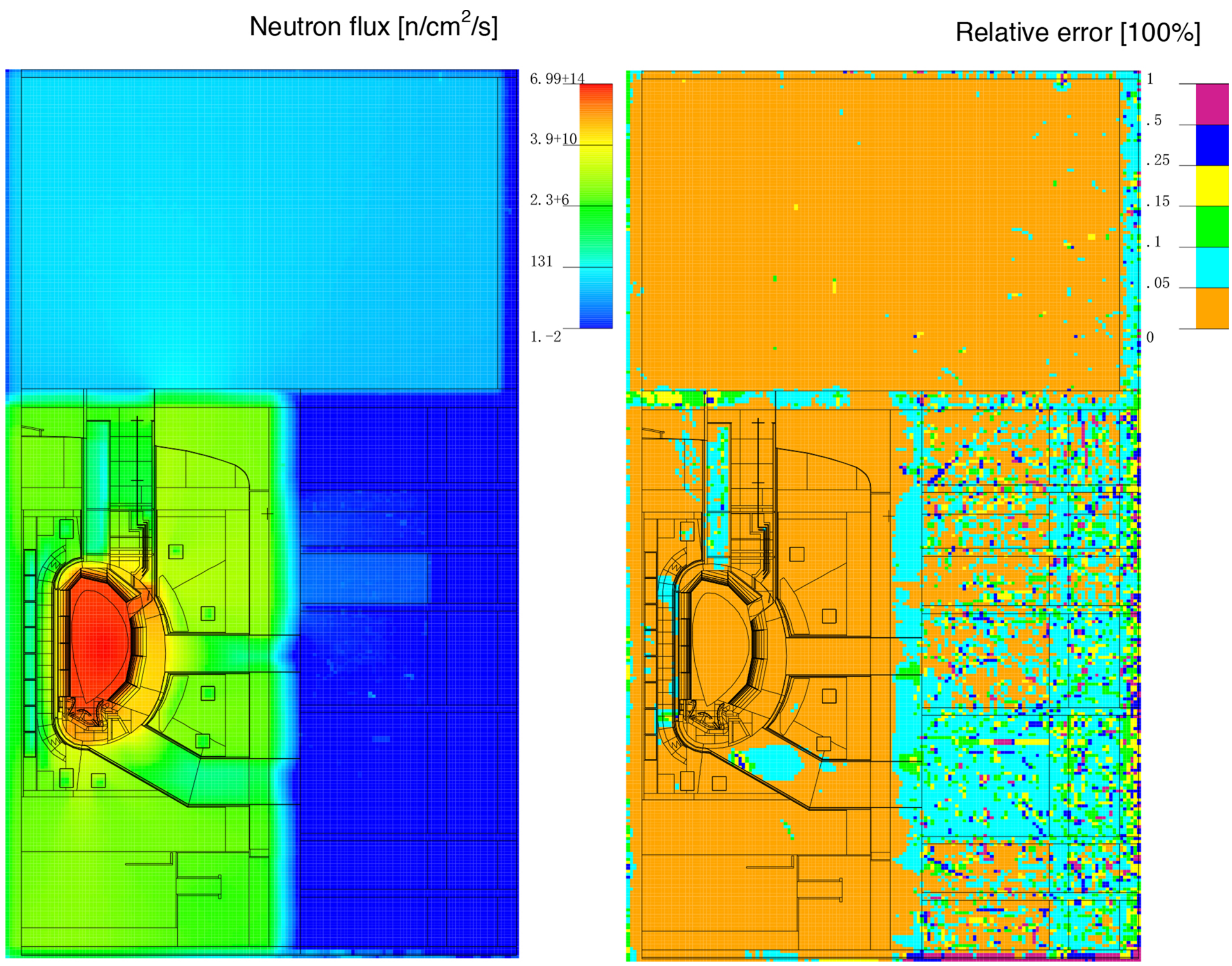

Fig. 4. Neutron flux distribution and statistic relative error.

5. Shutdown dose rate

An irradiation scenario of CFETR has been decided for the shutdown dose rate calculation on ECRH system considering the severest situation of neutron irradiation and activation. This irradiation scenario assumes CFETR runs 1 full power year (FPY) at 200 MW fusion power, 2 FPY at 500 MW, 5 FPY at 1 GW and last 2 FPY at 1.5 GW. The duty factor of CFETR is assumed 0.5 and full life time is 20 years. The activation level thus will be accounted for the whole life time.

Fig. 8 shows the dose rate at ECRH port 12 days after shutdown. Fig. 9 shows the time evolution of dose rate at position A, B and C of ECRH port. At ECRH port, it is planned to be maintained by workers. Thus the dose rate should be less than 100 μSv/h to meet the access allowance. At position A the dose rate is about 40 Sv/h 1 month after shutdown. At position B the dose rate is about 170 mSv/h 1 month after shutdown. At both position A and B the dose rate is beyond the limit for access. At position C, the dose rate is about 160 μSv/h 1 month after shutdown. This is still higher than 100 μSv/h but can be achieved by slightly changing of shielding design, then it could be allowed for access.

6. Conclusion

The operation and shutdown dose rate of CFETR has been calculated for nuclear safety evaluation. This analysis focuses on the ECRH heating system due to the blanket opening for transmitting the wave to plasma, which causes and increases to the neutron streaming, hence increasing the dose levels around the port and subsequently in the building itself. The neutronics model of ECRH and building has been integrated into the CFETR model by converting from the CAD to MCNP input with the support of McCad conversion tool. The advanced ‘on-the-fly’ global variance reduction technique has been used to generate the weight window for accelerating the particle transport.

The operation dose is calculated and normalized at fusion power of 1.5 GW. At ECRH port, the dose rate at bottom of port is extremely high due to the blanket opening, about 10^5 Sv/h. Due to the shielding of

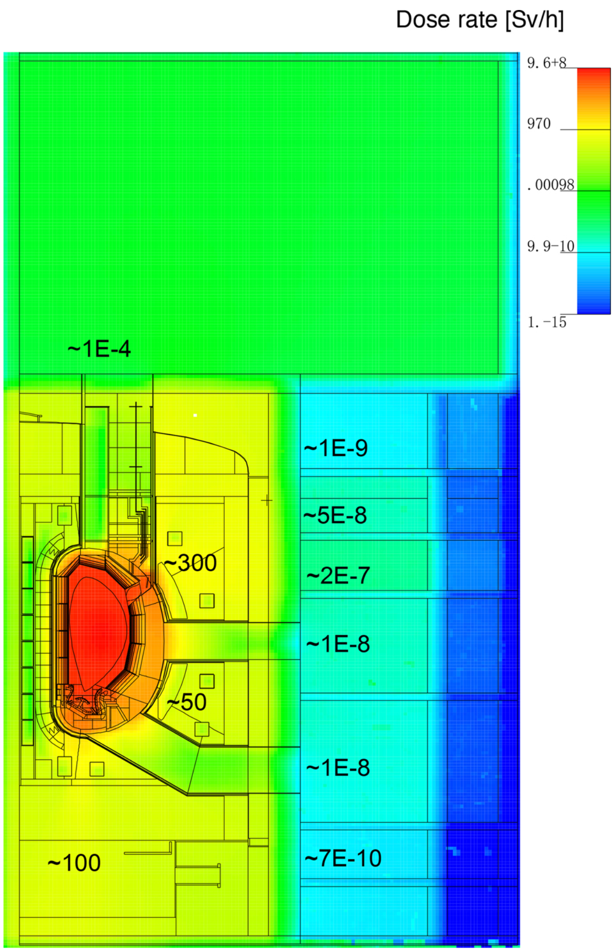

Fig. 5. Operation dose rate (Sv/h) of CFETR.

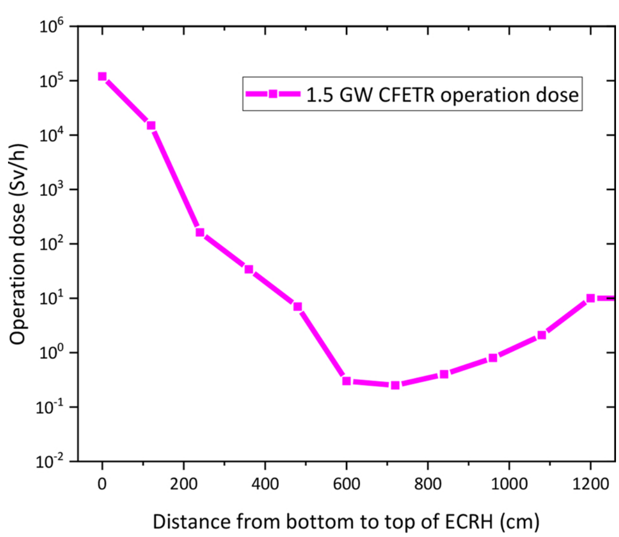

Fig. 6. Operation dose rate (Sv/h) of CFETR at ECRH port.

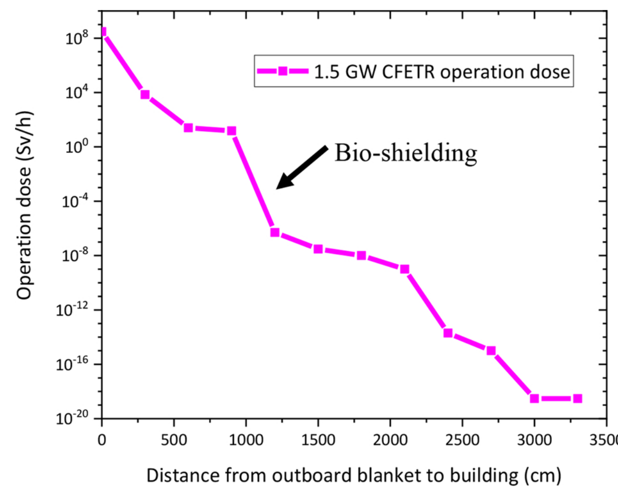

Fig. 7. Operation dose rate (Sv/h) of CFETR from outboard blanket to building.

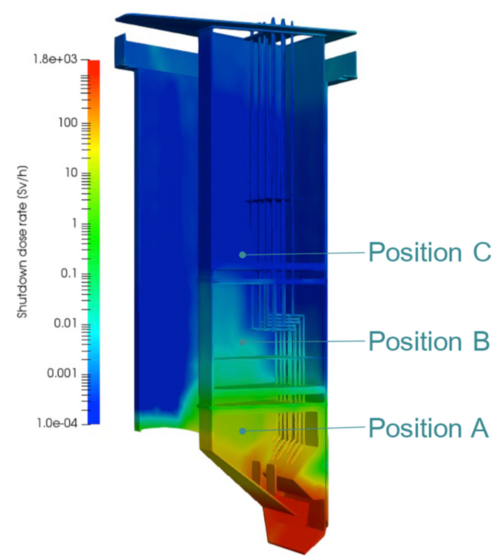

Fig. 8. The dose rate at ECRH port 12 days after shutdown.

support structure, the dose rate in the middle interspace decreases to 0.1 Sv/h. At top of port, the dose rate slightly increases to about 10 Sv/h due to the weak shielding of port outside the cryostat. In the building, the dose rate is extremely low less than 0.1 μSv/h, at most locations. Only in the building above ECRH port, the dose rate is about 100 μSv/h. According to the identification of CFETR radiological zone, it's yellow zone and should be limited for access by workers.

The shutdown dose rate is calculated under assumed irradiation scenario from 200 MW to 1.5 GW in 10 FPY. In the interspace of ECRH port, the dose rate at position A and B is too high for access by workers; at position C, the dose rate is about 160 μSv/h 1 month after shutdown. This is still higher than 100 μSv/h but can be achieved by slightly changing of shielding design, then it could be allowed for access.

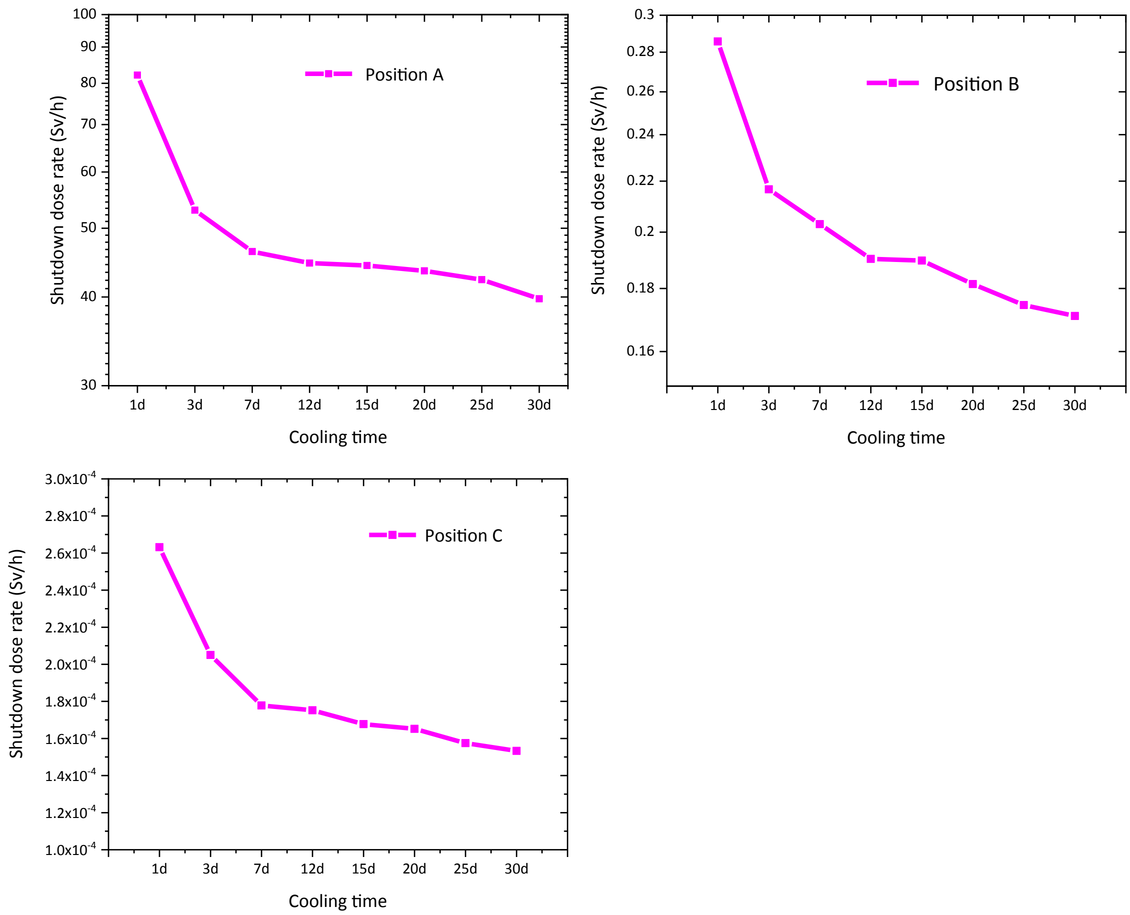

Fig. 9. Time evolution of shutdown dose rate at position A, B and C of ECRH.

CRediT authorship contribution statement

Peng Lu: Methodology, Software, Visualization, Writing - original draft, Writing - review & editing. **Qiuran Wu:** Investigation, Formal analysis, Validation, Writing - review & editing. **Liyuan Zhang:** Validation. **Yu Zheng:** Software. **Hua Du:** Software. **Kun Xu:** Software. **Songlin Liu:** Conceptualization, Supervision. **Xiaojie Wang:** Supervision, Resources. **Jianjun Huang:** Resources. **Bin Yu:** Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors gratefully acknowledge the discussion with Dr. Zizhao Zong from China Nuclear Power Engineering Co., Ltd for providing the information of radiological zone identification of CFETR. The authors wish to acknowledge the financial support of National Key R&D Program of China [grant number 2017YFE0300501], [grant number 2017YFE0300502], [grant number 2017YFE0300503].

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