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Activation analysis and radwaste assessment of CFETR

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ABSTRACT

The materials in the fusion system will be activated by the neutrons generated from D-T fusion reactions, causing the material with activity and decay heat at a variety level among the system. Predicting the amount of radwaste produced in the Chinese Fusion Engineering Testing Reactor (CFETR) and the time-evolution feature of the radwaste is of great importance to the minimization of waste and determine the management strategy. The purpose of this paper is to minimize the quality and quantity of the activated solid waste as low as reasonably achievable via source control, recycling and reuse, clearance, optimization of the management at the designing phase of CFETR. A detailed 3D model for CFETR is created to calculate the neutron spectra and fluxes of all non-void cells of the model. The inventory calculation for each cell with the given irradiation scenario and the cooling scheme was then carried out with FISPACT-II. The extensive calculation, data analysis, and post-processing are performed using a data processing code to calculate the component averaged activation responses and the waste classifications. The results suggest that the in-vessel materials exposed to high level neutron fluxes can hardly meet the clearance and low-level waste requirements, but they can be recycled with an advanced remote handling system shortly after shutdown or a conservative remote handling system after temporary storage within 100 years. The vacuum vessel, port plug, cryostat, and coils can be recycled with a conservative remote handling system with temporary storage. Especially, the port plug, cryostat, and central solenoid are clearable with temporary storage of 100 years. The influence of the operation time of in-vessel components on the radwaste severity and quantity is also evaluated. The severity of the radwaste increases when the operation time increases from 1000 to 3000 MWY, then decreasing with operation times longer than 3000 MWY. The detailed operation plan should be determined with comprehensive consideration of the important factors, including the influence on the radwaste severity. The allowed impurity level is also estimated, finding that the Uranium in the breeding zone and the SS316L used in divertor should be blamed for the intermediate-level waste production of blanket and divertor.

1. Introduction

The Chinese Fusion Engineering Testing Reactor (CFETR) is aiming to demonstrate fusion energy production up to 200 MW initially and to eventually reach DEMO relevant power level of more than 1 GW with tritium breeding ratio (TBR) > 1 [1,2]. The present parameters of the CFETR are major radius $R = 7.2$ m, minor radius $a = 2.2$ m, a specified plasma shape with the elongation κ of 2. There are several blanket candidates under evaluation, and this paper is focused on the Water Cooled Ceramic Breeding (WCCB) blanket concept. The up-to-date WCCB blanket that can satisfy multiple operation modes of CFETR with the fusion power of 0.2, 0.5, 1.0, and 1.5 GW has been designed at the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) [3].

A large amount of high energy (14 MeV) neutrons is generated from D-T fusion reactions during the operation of CFETR. The materials used in the fusion system will be activated by the neutrons irradiation, causing structural damage and activation, thus leading to activity and decay heat at a variety levels among the system. The radiation fields produced by the activated materials make worsen the operation, maintenance, and waste management at the end of the reactor (or component) life [4]. Inventory calculations can be used to predict the time evolution in composition, activation, and consequently the radiation fields for a given neutron irradiation scenario and material. The

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radiological response of the time-evolving material composition can then be used to assign a waste class to reactor components. The accurate inventory calculation plays an essential role in the radiation shielding design and waste management strategy of CFETR.

This work focuses on the solid radwaste of CFETR produced by neutron activation. The general objective of the waste management strategy is to minimize the quality and quantity as low as reasonably achievable via source control, recycling and reuse, clearance, optimization of the management method during the entire life cycle, designing, building, operation, and decommissioning of the fusion facility. Predicting the amount of radwaste produced from CFETR and the time-evolution feature of the radwaste is of great importance to minimizing waste and determining the management strategy. The present paper describes the activation results and the radwaste status of the main components for CFETR. The activity, decay heat at different times is calculated, and the radioactive waste management strategy for different components is discussed.

2. Calculations

A detailed 3D neutronic model is generated according to the up-to-date design of CFETR [2,3]. The neutron spectra and fluxes of all non-void cells of the model are calculated. The extensive calculation, data analysis, and post-processing are then performed using a data processing code NATF V1.8.0 [5], developed by ASIPP, to calculate the component-averaged activation responses and the waste classifications. The activation responses are used to evaluate the radioactive waste class (RWC) at different cooling times.

2.1. CFETR neutronic model

The main components, including blanket (BLK), divertor (DIV), vacuum vessel (VV), toroidal field coils (TFC), poloidal field coils (PFC), central solenoid (CS), thermal shield (TS), ports, cryostat, and supporting structures are represented in the neutronic model. Some supporting components, such as the supportive structure between blanket and vacuum vessel, are ignored as they will not influence the analysis too much and would not lead to overestimating the results. The 3D CAD model of the CFETR, as shown in Fig. 1, is built and imported into cosVMPT [6], a coding platform with the complete process of modeling, calculation, visualization, and generation of Monte Carlo transport code input file. A 22.5° section model with reflecting boundaries is used considering the symmetry geometry. An MCNP input file containing geometry and material definition was automatically generated and exported for transport simulations.

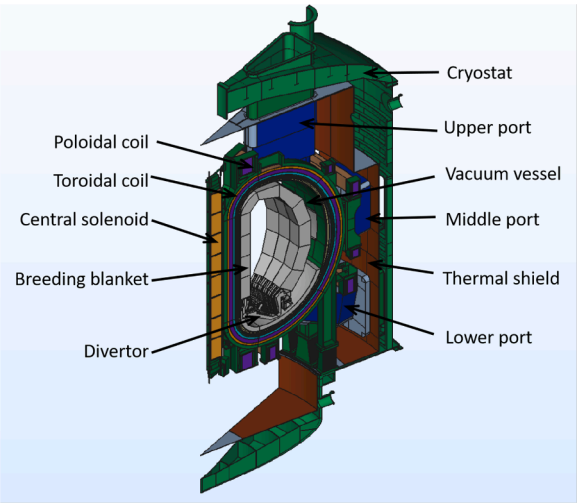


Fig. 1. Sketch of the 22.5° sector of CFETR.

Waste assessment of European DEMO highlighted the potential benefits of sub-dividing large components, for waste disposal and recycling prospects, in order to separate low activity regions of a component from more activated regions [7]. Therefore, most of the main components of CFETR are subdivided into smaller parts, after dismantling with remote handling systems, respecting the material composition and spatial location. For example, the WCCB blanket consists of 15 outboard modules (5 along the poloidal direction and 3 along the toroidal direction) and 12 inboard modules (6 along the poloidal direction and 2 along the toroidal direction) [8]. The WCCB blanket modules are represented in detail in the neutronic model. A WCCB blanket module consists of nine main components, including plasma-facing component (PFC), first wall (FW), breeding zone (BZ), cooling tube assembly (CTA), the manifold, radial-poloidal stiffening plate (rpSP), sidewall (SW), cover plates, and back supporting structure (BSS). The material compositions used of CFETR components are described in Table 1. The impurities and chemical compositions of the materials are described in Ref. [9]. The ODS steel [10] is used as the structure of the WCCB blanket in the up-to-date design.

2.2. Neutron transport

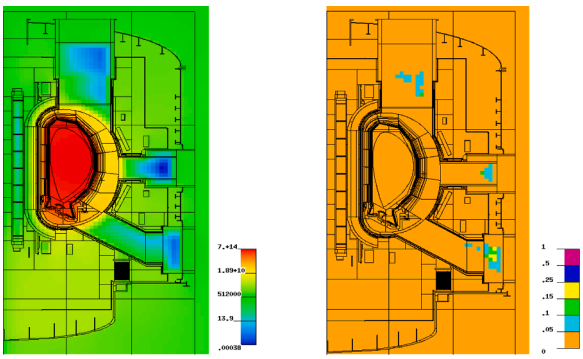
The accurate volumes of each non-void cell in the model are calculated using cosVMPT and used as the tally division for volume average neutron flux. The mass of each cell was computed by multiplication of the material densities and cosVMPT calculated volumes. DAG-MCNP5 [12] and FENDL3.1d data library [13] are used in the neutron transport simulation. An on-the-fly global variance reduction method [14] is used during the neutron transport. The neutron flux and spectrum of all non-void cells are calculated for detailed inventory calculation with a neutron transport simulation of 3×10^5 CPU minutes. The relative errors of the total flux for all cells are less than 0.01, which is accurate enough for neutronics analysis. The neutron flux and relative error map of CFETR under 1.5 GW is present in Fig. 2.

2.3. Inventory calculation

The NATF was used to write the FISPACT-II input files automatically using the necessary information from DAG-MCNP5 output files and other user-provided data, including the cell list for each group, irradiation scenario, detailed material composition with impurity, and the nuclides treatment before radwaste classification. The inventory

Table 1
The material composition of CFETR components.

Components		Material composition (vol%) [11]
Blanket	PFC	100% Tungsten
	FW	14.55% Water, 85.45% ODS steel
	BZ	14.4% Li_2TiO_3, 65.6% $Be_{12}Ti$, 20% He
	CTA	11.92% Water, 22.02% ODS steel, 9.51% Li_2TiO_3, 43.34% $Be_{12}Ti$, 13.21% He
	manifold	53.55% Water, 46.12% ODS steel, 0.33% He
	BSS	11.06% Water, 87.29% ODS steel, 1.65% He
	rpSP	14.97% Water, 85.03% ODS steel
	SW	29.09% Water, 70.91% ODS steel
	cover	2.18% Water, 96.23% ODS steel, 1.59% He
Divertor	First wall	59.23% Tungsten, 5.34% oxygen free copper (OFC), 6.76% CuZrCr, 12.03% Water, 16.64% ODS steel
	Structure	75% SS316L, 25% Water (150 °C, 5 MPa)
VV	Shell	SS316L(N)-IG
	Fill	10.29% SS316L(N)-IG, 89.71% Borated water
TF, CS	Case	SS316LN
	Conductor	Nb_3Sn
PF	Case	SS316LN
	Conductor	NbTi
Port	Plug	20%ODS steel+80%Water
TS		Borated steel
Cryostat		SS304/SS304L



(a) Neutron flux (n/cm^2·s) (b) Relative error

Fig. 2. Neutron flux at 1.5 GW fusion power.

calculation for each cell with the given irradiation scenario and the cooling scheme was then carried out with FISPACT-II.

The FISPACT-II inventory code [15] and EASY-II code system [16] are used to perform the inventory calculation. The assumed operation scenario of CFETR [17] is present in Table 2.

The in-vessel components are assumed to be replaced several times when they reach the design limits to ensure their structural and functional integrity. Currently, the detailed replacement plan has not been determined yet. In-vessel components are assumed to replace four times (including the initial installation) for the default case of the following analysis. The influence of the operation time of in-vessel components on radwaste management is also evaluated. As the fusion power of each operation phase is different, the equivalent operation time is determined, assuming that each replacement of the in-vessel components is exposed to the same neutron fluence of about 2300 MW · year. More specifically, taking the first installation of in-vessel components as an example, they are assumed to operate 1 full power year (FPY) under 200 MW, 2 FPY under 500 MW, and 1.1 FPY under 1000 MW before their dismantling.

Considering that the impurities in RAFM have an important radiological impact on the activation responses, thus making worse the level of radwaste [18–21], the detailed chemical composition with impurities [9] for in-vessel components are used in the inventory calculation. For the lack of data, the impurities in $Be_{12}Ti$ were derived from Beryllium S-65C VHP [9] according to the weight fraction. The impurities of the Nb_3Sn and NbTi are not yet considered. For one thing, the detailed impurities information are not currently available. For another thing, the impurities in Nb_3Ti and NbTi are not expected to make worse the severity of activity level, because the Nb itself causes much higher activity than other elements.

The activation responses of a variety of times after shutdown, range from 1 s to 10000 years, are calculated. The activation responses of each cell, such as activity, decay heat, alpha-heat, and contact dose rate, are extracted from FISPACT-II output files with NATF. A group that consists of a set of modeled cells is regarded as the unit of activation analysis and waste management. NATF performs sum (for volume, mass, total activity, etc.) or average (for specific activity, total decay heat, etc.) operation for the physical property and activation responses to get the equivalent unit of a group. A text file recording the cell list of each group is used to define the objects to be analyzed. A group may contain multiple sub-groups and cells, enabling the analysis at different scales from a single cell to the whole CFETR geometry or the analysis for specific materials distributed at different locations. For example, the blanket can be grouped module by module, allowing users to get the activation results for each module. Moreover, the blanket can be grouped component by component, such as BZ or FW, allowing the analysis of specific blanket components.

Table 2
Operation scenario of CFETR.

Fusion power (MW)	Equivalent operation time (years)
200	1
500	2
1000	5
1500	2

Separation of the components materials is one of the steps before management that may minimize the radwaste. Separate the VV of European DEMO is beneficial before disposal [21]. Therefore, the CFETR components are divided into smaller parts to get a more accurate assessment and better radwaste management strategy.

2.3.1. Nuclides treatment

The removal and extraction of tritium from the breeding blanket [22,23] as well as the detritiation of contaminated steel, due to the tritium generated by means of transmutations, is essential for fusion radwaste management. Furthermore, chemical or isotopic separation processes may be required for the manage route of such clearance and recycle [24–26].

The tritium extraction techniques and facilities for CFETR are under development [27–29]. The tritium produced in the breeding materials will be removed during reactor operation or shortly after shutdown. It is assumed that 99.9% of tritium of the blanket breeding zones is removed shortly after shutdown.

The trace amount of the tritium produced by transmutations in structural materials and that detained in breeding zones are likely to deteriorate the decommissioning process. Detritiation of the solid activated materials is necessary before the subsequent management. It is reported that tritium recovery rates from various materials, such as Be, SS316, Inconel 600, and Cu, are range from 97% to 99.9% by isotopic exchange with hydrogen [30]. The laboratory-scale experiments of process line showed that about 99% of tritium could be removed with a thermal treat with furnace under a flowing air atmosphere [31]. The detritiation efficiency is assumed to be 99% for the activated materials except for breeding zones.

The NATF provides nuclides treatment functions to simulate the effect of the detritiation and other isotope separation. A specific nuclide can be set to a wanted level for any cell or defined group. The 99.9% extraction efficiency at breeding zones and 99% detritiation rate are applied for all the data presented in this work.

2.4. Radwaste regulation

The radioactive waste regulation to which CFETR is subjected, is based on laws [32,33], governmental acts [34], departmental regulations (HAF401-1997, HAF402-2013), safety guides (HAD401 series). There are generally three categories of waste management routes in the Chinese regulation framework:

- Clearance. The waste with activity level equal or lower than clearance level, should be exempted from regulation.
- Recycling and reuse. Usually in the nuclear industry, recycling and reuse are foreseen when non-clearance waste with a certain activity level fulfills the requirement of remote handling recycling equipment.
- Disposal. For the waste that cannot be cleared or recycled, disposal, according to its waste classification, is foreseen.

The comprehensive radwaste management strategy that integrate clearance, recycling and disposal has been proposed and widely applied to fusion facilities like ITER, ARIES, and European DEMO [24–26,35,36]. The potential possibility of managing CFETR activated materials with the three routes is evaluated in the following sections. The indices of clearance, recycling, and waste levels under Chinese regulation are calculated for each component according to the correspondence limits

for each cooling time. Then the temporary storage requirement for a specific route and the quantity of radwaste allowed for each route is calculated.

There are several nuclear regulation authorities issued with clearance guidelines. The clearance standard of China is firstly addressed in Ref. [37] and updated in Ref. [34].

For the non-clearable components, recycling and reuse within the nuclear industry are preferred routes. There are generally three recycling methods: hands-on, conservative remote handling (CRH) and advanced remote handling (ARH). In this study, only recycling with remote handling systems is considered. The contact dose rate of the material is used to evaluate the remote handling requirement. The contact dose rate limits for CRH and ARH are 1×10^{-2} and 1×10^{4} Sv/h, respectively [24].

The waste classification standard of Chinese regulation [34] is derived from IAEA classification of radioactive waste [38] with specific quantitative values of allowable activity content for each significant radionuclide of each class. There are six classes of waste, exempt waste (EW), very short-lived waste (VSLW), very low-level waste (VLLW), low-level waste (LLW), intermediate-level waste (ILW), and high-level waste (HLW). Temporary storage of no more than 100 years is allowed under Chinese regulation for radwaste to decay to lower.

As for the scope of fusion facilities, it was assumed that no waste fell into HLW, which is based on the cooling requirements of waste generating significant decay heat when the material is released as waste [4]. VSLW is not considered, because the solid fusion radwaste derives mainly from materials activated by neutrons and contaminated by tritium, where the radionuclides have a half-life much longer than the very short-lived ones. The VLLW is not regarded as an individual class and merged into LLW, as it decays to EW with temporary storage. Therefore, this work focuses on only three classes: EW, LLW, and ILW under Chinese regulation:

1. EW: Material with an clearance index less than 1.
2. LLW: Material with activity below less than the limit given in Table 3.
3. ILW: Material with activities above the LLW limits.

The classification indices, such as the clearance index, are calculated with a "sum of fractions" rule to determine the class for wastes containing mixtures of the nuclides. The sum of fractions rule is applicable for the determination of LLW and ILW too. For comparison, the regulation and classification standards of UK [39], US regulation [40] with expanded limits by Fetter, etc. in Ref. [41], and the Russian regulation [42] are also used in this paper. Table 3 presents the permissible concentration of some nuclides for LLW under the regulations of China, Russian, and the US.

Table 3
Permissible concentration of some radionuclides for LLW.

Radionuclide	[a]China (Bq/kg)	[b]Russian (Bq/kg)	[c]US (Ci/m^3)
C-14	1×10^8	1.5×10^8	8
C-14 in activated metal	5×10^8	1.5×10^9	80
Ni-59 in activated metal	1×10^9	/	220
Ni-63	1×10^{10}	1.3×10^{10}	700
Ni-63 in activated metal	5×10^{10}	1.3×10^{11}	7000
Sr-90	1×10^9	1.3×10^{12}	7000
Nb-94 in activated metal	1×10^6	3.7×10^6	0.2
Tc-99	1×10^7	5.5×10^7	3
I-129	1×10^6	1.5×10^6	0.01
Cs-137	1×10^9	8.5×10^{10}	4600
Alpha emitting transuranic nuclides with half-life greater than 5 years	4×10^5	3.7×10^6	[d]3.7×10^6

[a] The limit of absent nuclides is 4×10^{11}Bq/kg [34];
[b] The values are estimated with bulk density of 2 t/m^3 in Ref. [42] and given in unit of Bq/m^3. They are converted to Bq/kg here for better comparison.
[c] The listed values are for Class C waste. Values for Class A or Class B waste have smaller limits [40]. All of Class A, B and C are regarded as LLW in this work.
[d] Unit is Bq/kg.

The LLW in the US regulation means radioactive waste that is not high-level radioactive waste, spent nuclear fuel, transuranic waste, byproduct material, or naturally occurring radioactive material [43]. There is no ILW labeling in the US regulation system. The Class A, B, and C waste, with increasing severity of the activity, are used for these LLW radwaste acceptable for near-surface disposal [40]. Therefore, for better comparison of the regulations, the radwaste satisfying the limits of class A, B and C are still denoted as LLW in this work, but the radwaste exceed the limits for class C is denoted as ILW.

The regulation of the UK, different from the others, categorize a material with α activity less than 4×10^6 Bq/kg and a combined $\beta + \gamma$ activity of less than 1.2×10^7 Bq/kg as LLW [39].

The Chinese regulation is generally more strict than that of Russian and the US as it allows fewer radionuclides concentration. And the UK regulation is even stricter than China.

3. Results and discussion

3.1. Radwaste classification

The total activity and decay heat of the main components at 1 s after shutdown of the CFETR is 3.85×10^{20} Bq and 1.82×10^3kW, respectively. The time-varying specific activity, decay heat density, contact dose rate, and the dominant nuclides are shown in Fig. 3.

The required temporary storage time for CFETR components to decay to clearance and recycle with CRH or ARH is present in Fig. 4. Most CS coils, port plugs, and cryostat can decay to clearance level with a cooling time of 10 to 100 years. There also exists a small portion of CS structure materials that decay to clearance level within 1 year. The rest components, including blanket, divertor, VV, TF, and PF coils, can not be cleared even after 1000 years. The mass of potentially cleanable material of CFETR is 6951.1 tonnes. The materials are also able to recycle with CRH after temporary storage between 1 to 100 years. All the materials can recycle with ARH shortly after detritiation.

The cooling time requirement for components to satisfy the limits to be classified as LLW is calculated and presented in Fig. 5. The vacuum vessel and ex-vessel components satisfy the LLW limits within 100 years under all the four radwaste classification standards. Most of the materials of blanket modules can not be classified as LLW under the regulation of China, Russian, and the UK. However, the blanket modules reach the LLW under the regulation of the US. The divertor exceeds the LLW limits after 1000 years because SS316L steel is used as the structure material.

As for a 100-year temporary storage time is limited, the total masses of the waste at the 100 years after shutdown are presented in Fig. 6. As the UK's regulation has the most strict requirement for LLW among these four regulations, and it has the most materials categorized as ILW. The waste classification results under Russian, the US, and China regulations are generally close to each other in terms of ILW after 100-year storage. More specifically, most of the CFETR main components are LLW, but the divertor is ILW.

3.2. Required temporary storage capacity

The temporary storage capacity for dismantled components during the operation and after shutdown in the hot cell is one of the problems for CFETR. The non-permanent components, including the blanket modules and divertor, should be transported to the hot cell after their

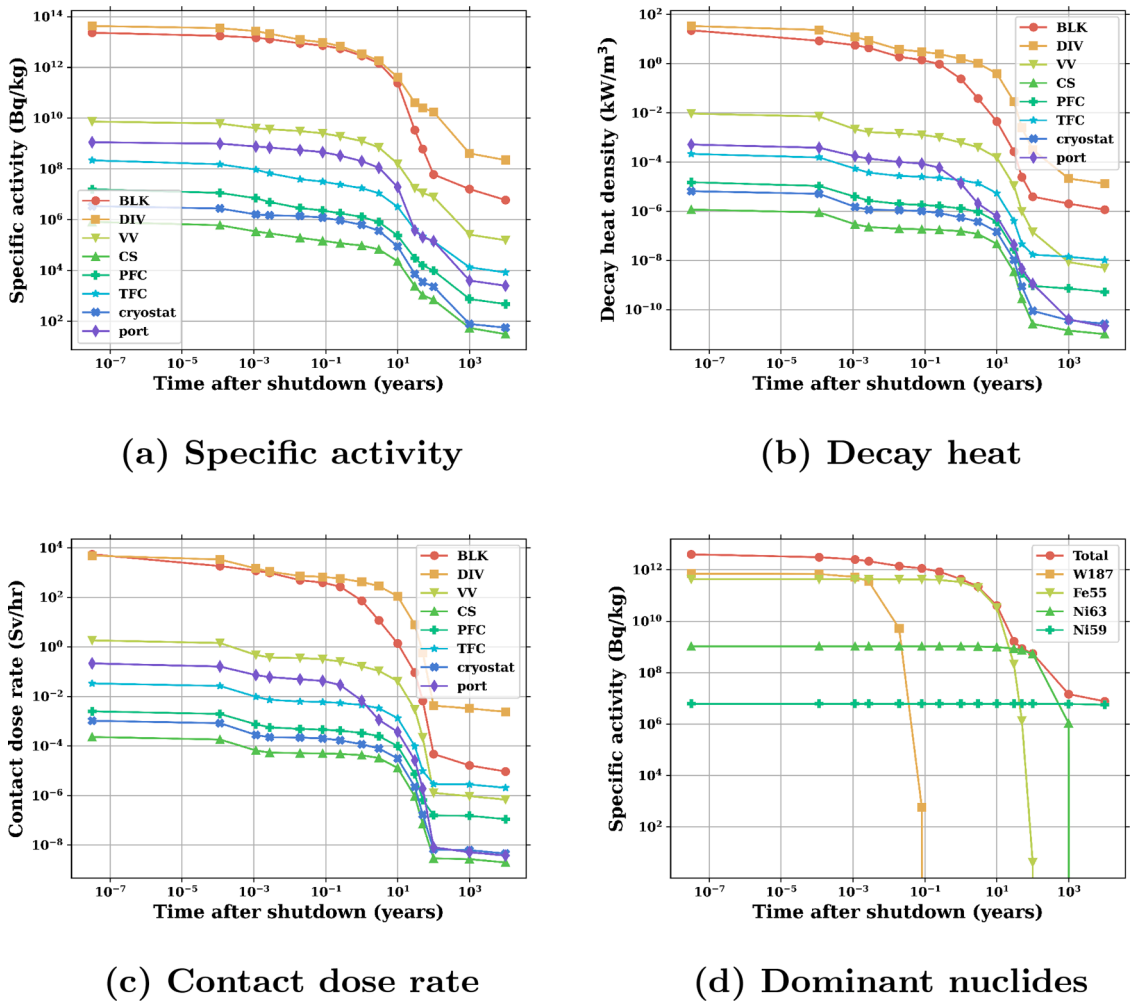


Fig. 3. Specific activity and decay heat density of CFETR main components after shutdown.

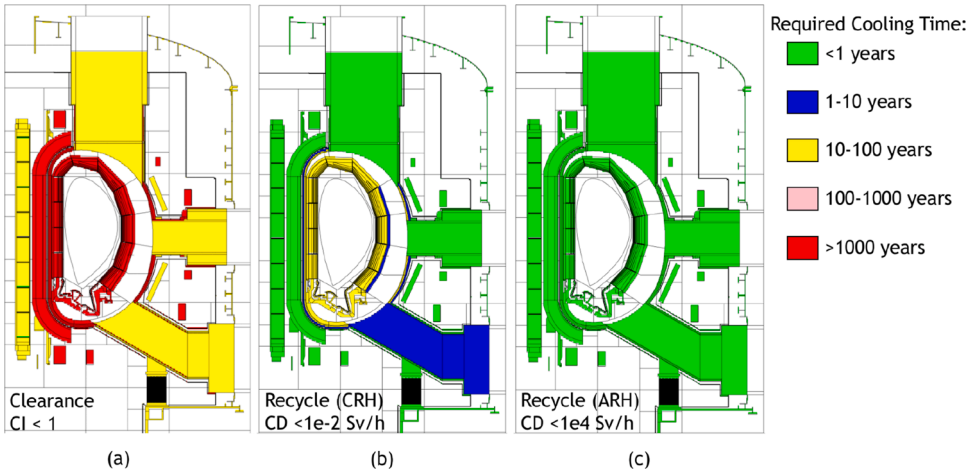


Fig. 4. Required cooling time for CFETR components to (a) clearance; (b) recycle with CRH; and (c) recycle with ARH.

replacement. Differently, the vacuum vessel, coils, and port plugs are permanent components that can be stored on-site. Therefore, the required temporary storage capacity in the hot cell for a relatively long time is blanket modules and divertor.

The activity level of radwaste changes with the temporary storage period because of the decay. The components in the hot cell can be removed out when they (a) decay to a level that meets the recycling requirement and transport to a recycling facility; (b) decay to LLW and transport to a near-surface disposal facility; (c) decay to clearance level and exempted from regulation. The amount of material in the hot cell increases gradually at the operation phase, and they can be moved out when they are recyclable, near-surface disposable, or clearance.

The evolution of the masses of in-vessel components at different activity levels is presented in Fig. 7. A certain of materials decay to LLW

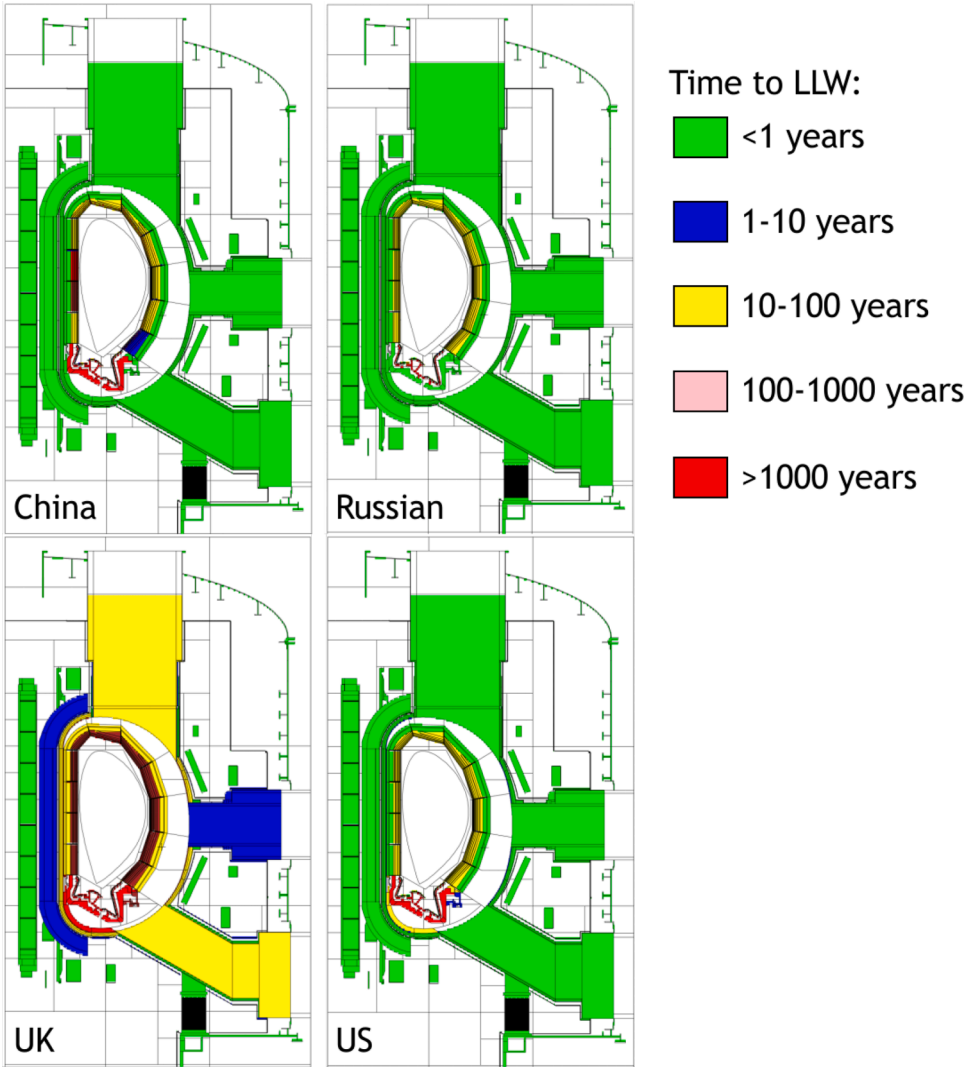


Fig. 5. Cooling time requirement for components to LLW under different radwaste regulations.

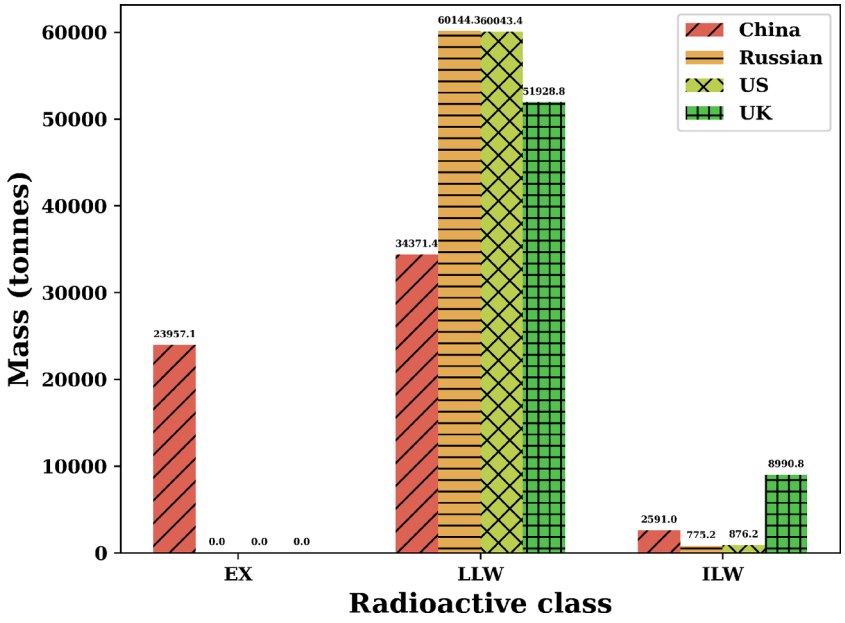


Fig. 6. The masses of radwaste under different classes after 100 years.

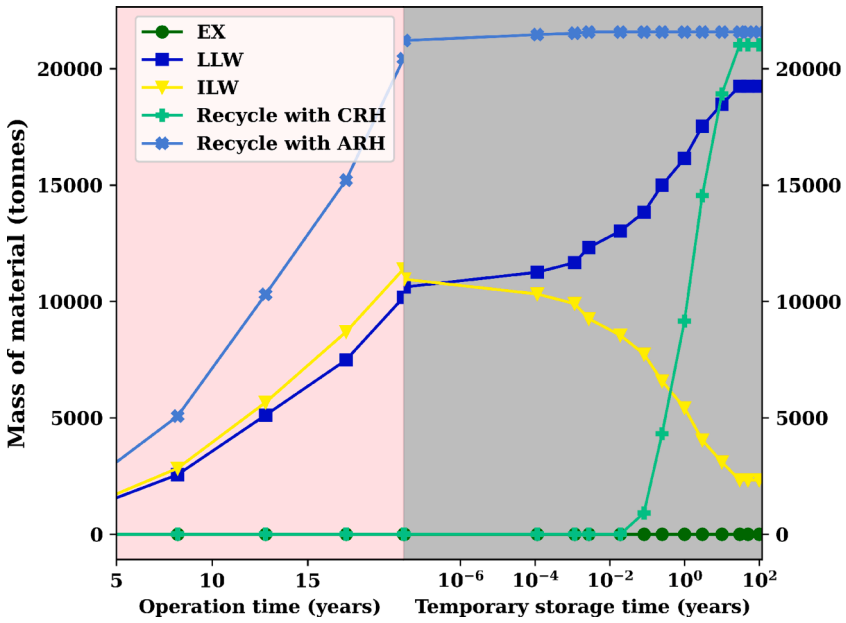


Fig. 7. Evolution of the masses of in-vessel components at different activity level.

and are recyclable with CRH in a short time, and the ILW amount is decreased from 5476 to 2330 tonnes after 100 years. Almost half of the in-vessel materials can be disposed of as LLW at the shutdown when subdivided into smaller parts. A shorter temporary storage period for radwaste before recycle or disposal means a smaller capacity requirement for the hot cell.

The temporary storage time needed for a component to decay to a specific activity level, such as CRH recyclable or cleanable level, influences the hot cell capacity requirement and management strategy. All the CFETR components (21572 tonnes), including the ILW, can be transported to recycle facility with advanced remote handling (ARH) system after a necessary process such as detritiation. Most of the materials (21021 tonnes), including all the LLW and part of the ILW, can be recycled after temporary storage of 50 years. Although not suggested, most of the blanket modules (19242 tonnes) decays into LLW classification and can be disposed with a near-surface facility. There is not any in-vessel material which decays to clearance level with 100-year temporary storage.

3.3. Influence of the operation time of in-vessel components

The blanket and divertor are exposed to intensive high energy neutrons during the operation, causing a relatively high level of damage and activity. To ensure the structural and functional integrity of the in-vessel components, they are assumed to operate only for a certain period and then are replaced. In Section 2.3, it is assumed that the in-vessel components would be replaced four times, with 2300 MWY for each replacement. The waste severity is decreased because of the lower dose, at the expense of increasing radwaste quantity, if the in-vessel components are replaced more often with a shorter operation time. Taking the divertor as an example, practically, it may be replaced more frequently, thus operating less time because of the high heat load and particle flux from plasma. Therefore, the neutron fluence of the divertor decreases, leading to less radionuclides production. Consequently, the waste severity of the divertor will decrease. However, less operation time and more replacement frequency indicate that the amount of radwaste from divertor is also increased. On the contrary, longer operation time and fewer replacements, if the allowed, increase the severity but reduce the quantity of the radwaste. Therefore, it is worth exploring the operation time limits to find a balance between the severity and the quantity.

The power times years is used here as the varying parameter to evaluate the influence of the operation time of in-vessel components because the CFETR runs under different power at a different phase. For example, the operation time of the first phase is 2 years under 200 MW with a duty factor of 0.5, here denoted as 200 MWY. The planned CFETR scenario runs at 9200 MWY in the lifetime operation. The masses of different radwaste classes after 100-year temporary storage are used to indicate the severity and quantity.

Figure 8 presents the masses change along with different in-vessel component operation time. The severity of the radwaste increases when the operation time increases from 1000∼3000 MWY, and the maximum ILW reaches about 5100 tonnes. The severity then gradually decreases when the operation time is longer than 3000 MWY. Although the activity level increases with the operation time, the in-vessel components replace only 1 or 2 times when it operates longer than 3000 MWY, the amount of the ILW decreases with the smaller replacement.

The results imply that let the in-vessel components operate about 5000 MWY or higher is more preferred than operating 2500∼5000 MWY, in terms of reducing both the severity and quantity of radwaste. Replacing the in-vessel components more frequently, after about 2000 MWY or less, can also reduce the ILW radwaste at the expense of significantly increase the amount of LLW waste. No doubt, many other factors might lead to component replacement, such as material degradation or functional deterioration. However, the detailed operation plan and the replacement schedule for in-vessel components should be determined under comprehensive considerations of the factors such as material durability under irradiation and the severity of the radwaste.

3.4. Impurity control

The undesired impurity in the material would lead to long-lived radioactive nuclides during the operation and aggravate the level of radwaste for a long time. The impurity of in-vessel materials should be reduced as low as reasonably as achievable to minimize the activity level of the radwaste. However, the divertor and part of the blanket structure become ILW even after a 100-year decay. It is helpful to evaluate the activation of these in-vessel components and optimize the material composition for radwaste minimization.

The average neutron flux of in-vessel components of CFETR is used to evaluate the reasonable impurity level for CFETR in-vessel components. Although the in-vessel components would not operate for the whole lifetime, a lifetime operation scenario of 9200 MWY with the neutron

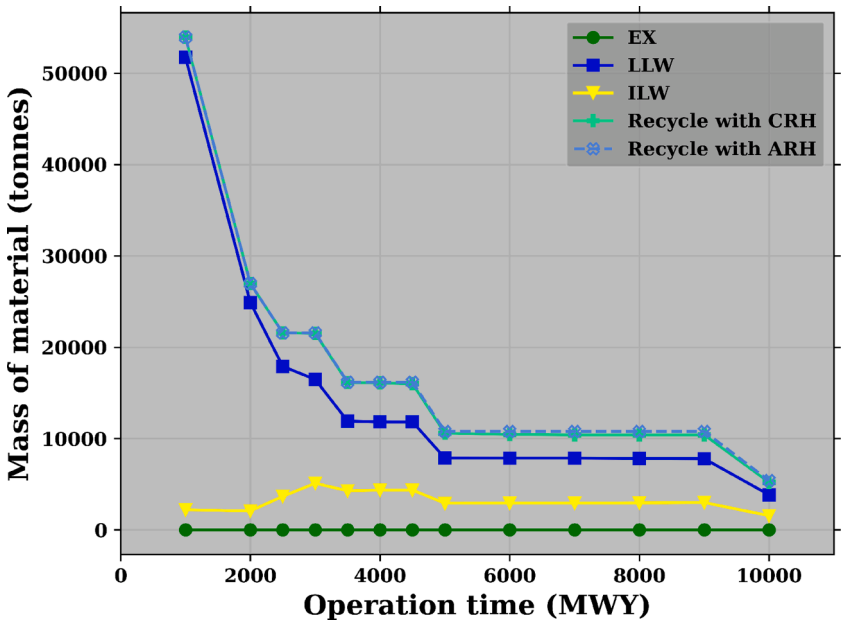


Fig. 8. Influence of the in-vessel components operation time on the radwaste severity and quantity after a 100-year temporary storage.

flux of out-board blanket FW at equatorial mid-plane is used to irradiate naturally existing elements to get a conservative estimation of the allowed impurity level. Then the specific activity and contact dose rate of each nuclide after a 100-year decay are used to evaluate the contribution to LLW index and contact dose rate with the help of NATF and pypact [44]. The allowed element mass fraction is calculated with the minimum value of the inverse of the LLW index and the limit for CRH (1×10^{-2} Sv/h) divided by contact dose index. The allowed impurity level for in-vessel components are presented in Fig. 9. Some nuclides, such as Li that produces tritium with a half-life of 12.32 years, should not be regarded as impurities when used as functional materials. The sum-of-fraction rule is applicable for impurity control too, the sum of the fraction of an element level divided by the allowed level should be no more than 1. Otherwise, the material would not be LLW or recyclable with CRH after 100-year storage.

The impurity that has the most impact on preventing the material recycling with CRH or disposal as LLW, can be found by comparing the material composition with the allowed impurity level. The 3.2×10^{-3} wt.% Uranium (U) in Be [9] makes the most contribution to the long-term activity of blanket radwaste. As the elements such as 1×10^{-1}

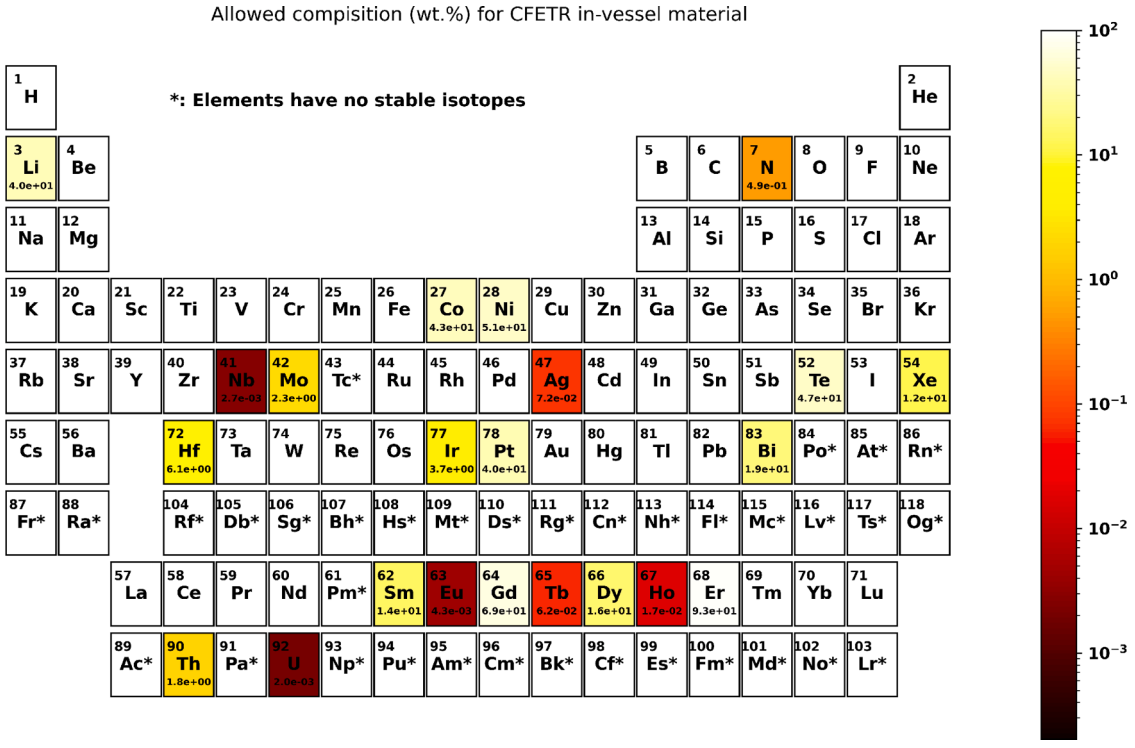


Fig. 9. Allowed impurity for CFETR in-vessel component if the material can be classified as LLW and recycled with CRH after temporary storage of 100 years. The level of some high activation impurity are noted below the element symbol in unit of wt.%.

wt.% Nb, 12.25% Ni, 2.5% Mo in SS316L [9] is to be blamed for the relative high level radioactivity of divertor. It is also suggested to replace the material of divertor structure from SS316L to RAFM, such as ODS steel.

4. Summary

The neutron transport and inventory simulations have been performed for the components of CFETR. The activation responses, including the activity, decay heat, and contact dose rate of the components, are calculated and used to determine the radwaste class under the regulation of China.

The total activity at the shutdown of CFETR is about 3.85×10^{20}Bq. The components of the CFETR are classified into different groups according to the neutron flux level and material. The blanket and divertor have the highest level of radioactivity after the irradiation of several operation years. The management strategy for the activated material, including clearance, recycling with conservative or advanced remote handling system, disposal as low-level waste, or intermediate-level waste, are assessed.

The results show that some ex-vessel components can be cleared within temporary storage on-site. The in-vessel components, including blanket and divertor, however, are not able to clearance. The blanket and divertor are planned to be dismantled, detritiated, and temporarily stored in hot cell after several years of operation. Almost all the material (21021 tonnes) can be recycled with a conservative remote handling system after temporary storage of 50 years. Although it is not suggested, most of the in-vessel components can dispose as LLW.

The influence of the operation time of in-vessel components on the radwaste severity and quantity is also evaluated. The severity of the radwaste increases when the operation time increases from 1000∼3000 MWY and the maximum ILW reaches about 5100 tonnes and then decreases when the operation time is longer than 3000 MWY. Although the activity level increases with the operation time, the in-vessel components replace only 1 or 2 times when it operates longer than 3000 MWY, the amount of the ILW decreases with the smaller replacement. The detailed operation plan should be determined with comprehensive consideration of the crucial factors, including the influence on the radwaste severity. The allowed impurity level is also estimated based on their influence on the manage routes of recycling with CRH and disposal as LLW. It is found that the U in the breeding zone and the SS316L used in divertor should be blamed for the ILW production of blanket and divertor.

The safety requirement of temporary storage of the in-vessel components in the hot-cell, such as the cooling and radioactive containment, will be assessed in the future work. The activation responses and the radwaste caused by the neutrons and photons decay from the secondary irradiation in blanket coolant will also be assessed.

CRediT authorship contribution statement

Xiaokang Zhang: Methodology, Software, Investigation, Writing – original draft. **Qiuran Wu:** Conceptualization. **Hua Du:** Software. **Yu Zheng:** Software. **Peng Lu:** Writing – review & editing. **Songlin Liu:** Conceptualization, Supervision.

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.

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