INTRODUCTION

Massive conventional energy consumption put great burden on environment and human health, for example, global warming due to energy-related carbon emissions. New energy technologies and policies are becoming hot topics and are expected to meet the energy demand and to be environment-friendly. Nuclear fusion is regarded as an important option.
for a clean and safe solution for our future long-term energy needs.\textsuperscript{5} More and more human and financial resources are being put into the fusion research.\textsuperscript{6} As the largest international energy cooperation project including seven members, the International Thermonuclear Experimental Reactor (ITER) located at Cadarache in France is being constructed. It is expected to achieve the first plasma in December 2025 and deuterium-tritium (DT) operation in 2035.\textsuperscript{7} Meanwhile, the next fusion reactors were also proposed and supported by many national and local governments based on the roadmap of fusion energy development. Two kinds of strategies were identified. The first is to build a smaller sized fusion experimental facility before building a fusion power plant. China proposed a concept of Chinese Fusion Engineering Test Reactor (CFETR).\textsuperscript{8,9} the USA proposed a concept of Fusion Nuclear Science Facility (FNSF).\textsuperscript{10} The others are to build a DEMOnstration fusion reactor (DEMO) with over 1500 MW fusion power to produce electricity directly. EU-DEMO, K-DEMO were proposed by Europe and Korea, respectively.\textsuperscript{11,12}

Deuterium and tritium have been regarded as the fuels for the above-mentioned fusion reactors because DT fusion reaction requires the lowest fusion triple product to achieve energy self-sustaining among various fuels fusion reaction. For a fusion reactor with 1 GW fusion power, about 37.1 kg deuterium and 55.6 kg tritium would be burnt per full power operational year.\textsuperscript{13} Deuterium resource is abundant while tritium resource is scarce. For tritium, the only significant national sources are cosmic rays passing through the Earth’s atmosphere and possibly accretion from the solar wind. An equilibrium quantity of \( \sim 3.5 \) kg is present from these sources.\textsuperscript{14} The commercial tritium consumption is mainly from the artificial generation. Tritium price of Heavy Water Reactor (HWR) production is relative low compared with other tritium production pathways of accelerator and light water reactors.\textsuperscript{15} Currently, most of the commercial tritium are from CANadian Deuterium Uranium reactors (CANDU) of Canada and Korea where Tritium Removal Facilities (TRF) are being operated. India has also positive plans to build CANDU reactors and may be the promising country with a high tritium generation rate if operating the TRF in the future. Both our early study and recent studies evaluated the worldwide tritium resources available for fusion reactors and showed the worldwide tritium generated from CANDU reactors may be insufficient for start-up, let alone as burning fuels for next fusion reactors.\textsuperscript{15-17} Thus, start-up and tritium self-sufficiency is critical important for an economical fusion energy.

ITER is only designed to test tritium breeding using three ports to install six tritium breeding blanket modules.\textsuperscript{18,19} Tritium self-sufficiency cannot be fully validated just through the construction of ITER device. Thus, tritium self-sufficiency is one of the key issues remained to be solved in the next fusion reactors. Both of the fusion engineering test reactors and fusion demonstration reactors are being designed to achieve the target of tritium self-sufficiency.\textsuperscript{8,10-12} In China, the engineering design phase of CFETR has begun and would be hopefully completed around 2020, which will support the proposal for construction phase according to the recent roadmap. The reactor start-up and tritium self-sufficiency issues should be discussed for CFETR during its engineering design phase considering the uncertainties of tritium resources available and existing risk of failing tritium self-sufficiency.\textsuperscript{9,20,21} The objectives of this work are as follows: (a) to introduce the preliminary fuel cycle concept and available tritium resources for CFETR, (b) to evaluate and discuss the tritium demand for CFETR start-up (phase I: 200 MW) and the feasibility of DD start-up, (c) to identify the possible pathways to tritium self-sufficiency through sensitivity analysis based on the design baseline of CFETR, (d) to evaluate the consequences in case of failing tritium self-sufficiency, and (e) to identify the future R&D needed for tritium self-sufficiency. It is expected to give insights into the question on how to start the reactor in a more economical way, into the feasibility of tritium self-sufficiency, and what will happen in case of failing tritium self-sufficiency. The structure of the article is as follows. Section 2 introduces the preliminary fuel cycle concept and model for CFETR. Section 3 describes the fuel start-up for CFETR to answer how to start CFETR more economically. Section 4 discusses the tritium self-sufficiency analysis and future R&D needed to answer what about the feasibility of tritium self-sufficiency, what will happen in case of failing tritium self-sufficiency, and how to do in the future. Finally, conclusions are given in Section 5.
plant system, tritium recovery, and recycling technology for plasma exhaust gas of CFETR, tritium extraction, and measurement engineering technology for breeding blanket of CFETR.22

2.2 | Preliminary fuel cycle concept

The fuel cycle concept of CFETR is mainly proposed to be based on R&D experiences of ITER fuel cycle.22-24 For ITER, the tritium fueling into the vacuum vessel is burnt partly and most of the tritium will be pumped out accompanied by deuterium, helium, and other impurities. The cyclic utilization of tritium is necessary and the tritium will be extracted from exhausted gas in a tritium plant. To ensure the achievable of target fusion power, equal percent fuels (50:50 mix of DT) were adopted in all fueling systems of ITER.25 The equal percent fuels required the Isotope Separation System (ISS) essential in the fuel cycle path. Then the cyclic tritium can be re-injected into the vacuum vessel by the fueling system.

For CFETR, a modified fuel cycle concept was proposed to increase fuel cycle efficiency and further decrease tritium inventory in the tritium building.22 For the inner fuel cycle, the major difference is that the ISS would not be the main path in the fuel cycle. The helium and impurities of fuels pumped out from vacuum vessel would be removed through the Tokamak Exhaust Processing system (TEP), then the mixed fuels would be re-injected into the vacuum vessel directly through the tritium Storage and Delivery System (SDS). The small remained tritium in the exhaust of TEP would be separated using ISS to control tritium emission from safety consideration. In addition to the above, some design optimization was proposed to realize the quick removal, such as the gas chromatography technology.22 For the outer fuel cycle, a stable Tritium Extraction System (TES) would be used for tritium extraction from the blanket. The extracted tritium should also be processed before fueling into the reactor. A separate ISS was designed to ease the burden of the inner cycling loop because the features of hydrogen isotope separation between the inner and outer fuel cycle are very different, such as about equal percent of DT in exhaust of inner fuel cycle while nearly no D in the outer fuel cycle.22 Both the inner and the outer fuel cycle of CFETR are shown as simple block diagram in Figure 1.

2.3 | Mixed fuel burning and cycle model

For CFETR, a mixed fuel burning including DD, DT and D³He would appear in the plasma if failing the 50:50 DT mixed fuels. In this case, a steady-state fuel burning with a certain fusion power could still be achieved at least, and the evaluation results are shown in the following part. To evaluate the fuel cycle and tritium self-sufficiency, a mass flow model of fuels for CFETR was developed using the system dynamics platform named STELLA.26-28 The advantage of the model was visual fuels flow compared with early model using programming language. The key formulas in the model are shown as follows.

Based on principle of mass conservation and the mean residence time method, the general system dynamics model for each subsystem in fusion fuel cycle is shown in formula (1).

\[
\frac{dI_i}{dt} = \sum_{j=1}^{m} \frac{I_{j\rightarrow i}}{T_j} - \sum_{k=1}^{n} \frac{I_{i\rightarrow k}}{T_i} - \lambda I_i - P_i(t) I_i - f I_i
\]

(1)

where \(I_i\) is tritium inventory in \(i\) subsystem, \(T_i\) is the residence time of \(i\) subsystem, \(\lambda\) is the decay constant, \(P_i(t)\) is permeation rate, \(f\) is tritium burn-up fraction in plasma.

The formula (1) is used to calculate the tritium inventory in the plasma (vacuum vessel) shown in Figure 1 considering the factors of total throughput, exhaust, decay, permeation into the PFM and burning. For other subsystems in tritium plant such as TEP, ISS, the burning factor is set as zero.

The fuels (T, ³He, D) burn-up fraction in plasma \(f\) is described in formulas (2) (3) and (4).29

\[
f_T = \frac{1}{1 + \left(\frac{n_D \tau_T (\sigma v)_{DT}}{\nu}\right)^{-1}}
\]

(2)
where $n$ is ion density, $\tau$ is ion confinement time, $\sigma v$ is the reaction rate. It should be noted that in formulas (2) (3) and (4), the $f_T$ means the ratio of the amount of tritium consumed in fusion reactions every second to the total tritium we lose every second in the burning plasma (tritium ions escaping from the last closed flux surface of the tokamak and never returning again). However, the tritium burn-up fraction of ITER was defined as the ratio of tritium amount of tritium consumed in fusion reactions every second to the total tritium throughput (fueling) amount every second (the total throughput including five factors: replenishing the burnt tritium, replenishing the particle transport loss, replenishing the loss because of triggering the ELM frequency for reducing the ELM energy loss, controlling the peak power load on the divertor plates by auxiliary neutral gas fueling flux). This means the tritium burn-up fraction definition of ITER has considered the fueling efficiency factor ($f_T \times$ tritium fueling efficiency). In the following part, the tritium burn-up fraction definition of ITER was used to perform the analysis.

Based on the basic modeling and definition of tritium burn-up fraction, the tritium start-up amount and tritium self-sufficiency definition are described in formulas (5) and (6), respectively. Detailed descriptions were shown in Section 4.

$$f_{He} = \frac{1}{1 + (n_D \tau_{He}^3 (\sigma v)^D_{He})^{-1}}$$

$$f_D = \frac{1}{1 + (n_E \tau_D^3 (\sigma v)^D_{He})^{-1}} + \frac{1}{1 + (n_D \tau_D^3 (\sigma v)^D_{He})^{-1}} + \frac{1}{1 + (n_{He} \tau_D^3 (\sigma v)^D_{He})^{-1}}$$

$$m_{\text{start-up}} = \frac{t_{\text{cycle}} \times m_{\text{burn-rate}}}{f_T}$$

$$\text{TBR}_{\text{ach.}} = \text{TBR}_{\text{req.}} + \frac{(m_{\text{start-up}} + m_{\text{retention}}) \times R_{\text{decay}} + m_{\text{release}} + m_{\text{disposal}}}{m_{\text{burn-rate}} \times t_{\text{burn-time}}}$$

where $m_{\text{start-up}}$ is tritium start-up amount (not including the tritium retention in materials in the initial operational phase), $t_{\text{cycle}}$ is tritium cycle time, $m_{\text{burn-rate}}$ is tritium burn rate, $m_{\text{retention}}$ is tritium retention amount in the materials of whole fusion system, $R_{\text{decay}}$ is tritium decay rate, $m_{\text{release}}$ is tritium release amount into the environment, $m_{\text{disposal}}$ is tritium disposal amount along with waste, $t_{\text{burn-time}}$ is tritium burn time of fusion reactor in a given period.

### 3 | FUEL START-UP FOR CFETR

#### 3.1 | Tritium start-up demand

The tritium start-up amount is mainly influenced by the tritium burn-up fraction and the cycle time for a fusion reactor with a certain fusion power. Regarding the CFETR phase I, the fusion power is 200 MW which corresponds a tritium burning rate as $3.5 \times 10^{-4}$ g/s. Tritium burn-up fraction is the ratio of tritium burning rate to tritium fueling rate. According to R&D experiences of ITER, the tritium fueling rate can be affected by many factors to maintain the operation of a fusion reactor. To maintain the equal share of deuterium and tritium in plasma, equal percent fuel was adopted in all fueling systems of ITER. Thus, the tritium fueling will contribute to all fueling requirements: substitute the burnt tritium, substitute the particle transport loss, substitute the Edge Localized Modes (ELM) loss, and so on. For ITER, the maximum tritium fueling rate is 100 Pam$^{-3}$ s$^{-1}$, and the tritium burning rate is 0.35 Pam$^{-3}$ s$^{-1}$. Thus, a conservative 0.35% of burn-up fraction was regarded to be achieved in ITER under the condition 50:50 mix of DT. In an optimistic scenario, the tritium burn-up fraction can reach about 1% if only tritium fueling is used for replenishing the burnt tritium and particle transport loss and deuterium fueling for other fueling requirements, for example, triggering the ELM frequency for reducing the ELM energy loss, controlling the peak power load on the divertor plates, as they do not contribute too much to the fueling for the core plasma burning. For tritium cycle time, early tritium cycle modeling studies always assumed 24 hours which referred to Tritium Systems Test Assembly (TSTA) results at Los Alamos National Lab (LANL) in 1986. In recent studies, an ambitious goal for tritium recycle has been set as 1 hour for ITER tritium plant design. Due to the comparable but different tritium fuel cycle of CFETR, the state-of-art prediction for CFETR was 2-6 hours. Those predictions of tritium burn-up fraction and tritium cycle time will be validated in future ITER experiments.

To give a broad discussion, a sensitivity analysis of tritium start-up amount for CFETR was performed. The results are shown in Figure 2. They are based on the baseline parameters of fusion power (200 MW), tritium cycle time (4 hours), and tritium burn-up fraction (1%) using formula (5). It is clear that the tritium start-up amount requirement is about 500-1500 g if tritium cycle time and tritium burn-up fraction are controlled as 2-6 hours and 1%, respectively. From the engineering design viewpoint, the tritium start-up amount should be larger than the calculated value as some of tritium would be retained in the materials of vacuum vessel, tritium plant, and other pipes even in the initial operational phase. The research on dynamic initial tritium retention in the whole system is being conducted using COMSOL Multiphysics and EcosimPro platform.
Feasibility of DD start-up

Under the pessimistic scenario of commercial tritium resources available, it seems no way to purchase enough tritium from CANDU reactors abroad for CFETR tritium start-up. A solution named DD start-up that fusion reactor could be started up only fueling with initial deuterium was proposed. Several studies evaluated the feasibility of DD start-up future fusion reactors. Regarding CFETR phase I, dynamic ion density and fusion power in its initial start-up phase was estimated based on the parameters in Table 1.

The results of the estimation are shown in Figure 3. It can be seen that (a) D and T ion density will reach steady state after operation for a certain time without initial tritium supply. For CFETR, it needs about 2-3 years to reach steady-state ion density. The time depends on Tritium Breeding Ratio (TBR), tritium cycle time and fusion energy, etc.; (b) The ratio of D and T ion density depends on TBR when the ion density reaches steady state. The higher TBR is (before tritium self-sufficiency), the nearer a ratio of deuterium and tritium ion density approximates to 1.0. When the achievable TBR is higher than the required TBR of tritium self-sufficiency, the ratio is equal to 1.0; (c) A steady-state fusion power could be achieved even without initial tritium resources. And the steady-state fusion power at last depends on TBR (irrespective of whether tritium self-sufficiency is reached or not). Full power could be reached under the steady-state power operation if CFETR could achieve tritium self-sufficiency. On the other hand, if failing tritium self-sufficiency, for example, TBR = 0.99, full power could never be reached.

It is clearly visible from Figure 3B that the DD start-up would cause a fusion power loss for the fusion reactor in the initial phase, and that the fusion power loss corresponds to a benefits loss. On the other hand, purchasing the tritium for start-up would also require about US$(1.25-3.75) \times 10^7$ according to the tritium start-up amount of 500-1500 g and the current tritium price of US$25 million/kg. The question which way is more economical one was also evaluated. For the TBR = 1.17, the benefits loss due to fusion power loss would be about US$3.71 \times 10^7$ regarding the ratio of electric

**TABLE 1** Basic design parameters of CFETR for mixed fuel cycle evaluation

| Parameters                          | Value          |
|-------------------------------------|----------------|
| Fusion power                        | 200 MW         |
| Plasma temperature                  | 12.65 keV      |
| Electron density                    | $1.22 \times 10^{20}$ m$^{-3}$ |
| Ratio to Greenwald density limit    | 0.82           |
| Plasma volume                       | 576 m$^3$      |
| Energy confinement time             | 1.10 s         |
| Tritium cycle time                  | 6 h            |
| Assumed tritium nonradioactivity loss| 0.1%           |
| Assumed tritium breeding rate of DT neutron | 0.99-1.17   |

**FIGURE 2** Tritium start-up amount of CFETR vs tritium burn-up fraction and tritium cycle time. The curve 1 is based on tritium cycle time of 4 h and the curve 2 is based on tritium burn-up fraction of 1%

**FIGURE 3** Initial dynamic ion density (A) and fusion power (B) for DD start-up of CFETR with different Tritium Breeding Ratio
power and fusion power as 47% and the grid purchase electricity price in China as US$0.057 per kW·h. For the condition with higher TBR, the benefits loss would be decreased as the higher TBR would achieve full power earlier. Thus, both of the two ways for CFETR start-up are almost equivalent economical.

Both considering the factors of economy and tritium resources available, the DD start-up solution for CFETR or other fusion reactors would be more reasonably as long as the tritium price could not be greatly decreased in the future.

4 | TRITIUM SELF-SUFFICIENCY ANALYSIS AND FUTURE R&D NEEDED

4.1 | Definition of tritium self-sufficiency and main design parameters of CFETR

The tritium self-sufficiency is defined if the achieved TBR is not less than the required TBR, or if the tritium production is not less than the tritium consumption. The tritium production depends on the global blanket breeding design. The tritium consumption includes three parts. The first is tritium burning in the plasma. The second is tritium decay which depends on tritium inventory (flow and retention) in the whole fusion system. The third is tritium nonradioactivity loss, for example, part of tritium retained in the fusion materials and finally regarded as radioactive waste without recycle. The definition of tritium self-sufficiency and the required TBR was shown and calculated using the formula (6).

To evaluate the feasibility of tritium self-sufficiency for CFETR, some baseline designed parameters were shown in Table 2. The tritium burn-up fraction and tritium cycle time have been discussed in the previous part. The burning availability of 30%-50% is the design target of CFETR. Regarding the tritium retention in fusion materials, a global simulation should be performed exactly. The maximum tritium retention amount in Plasma Faced Materials (PFM: tungsten) would be higher than 1 kg based on previous evaluation when reaching steady tritium concentrations. However, based on ITER experiences, a safety limit of 1 kg was set from the public safety as well from a reasonable operational domain consideration. To ensure public safety, it is self-evident to set the same safety limit for CFETR. It is not exactly known how much tritium will be retained in the blanket materials and tritium plant materials of CFETR. Based on ITER experiences, it seems that the tritium retention in tritium plant materials would be less than 1 kg. For tritium retention in blankets, a very rough estimate has been performed for ARIES advanced power plants, and the results showed that the maximum tritium retention amount was about 2 kg for ceramic breeder blankets. Thus, referred to the data above, the maximum tritium inventory in the whole system of CFETR would be about 4.5-5.5 kg, which is slightly higher than ITER. The tritium inventory corresponds to a decay loss rate of 246-301 g/a.

Other factor of nonradioactivity loss can be determined only after finishing the detailed engineering design of de-tritiation systems and treatment methods of tritiated waste. If assuming that the lifetime of these components is 5 years and de-tritiation techniques could achieve 95% of tritium removal and recycling before the final disposal, the nonradioactivity loss rate would be about 40 g/a. Another tritium nonradioactivity pathway is the normal emission into the air, and the emission rate is about 0.6 g/a based on ITER experiences.

4.2 | Required TBR for tritium self-sufficiency

According to the preliminary estimation, tritium decay and nonradioactivity loss rate is about 287-342 g/a. Thus, the net tritium breeding rate should be no less than the value to achieve tritium self-sufficiency. For CFETR phase I with a fusion power of 200 MW and burning availability of 30%-50%, the tritium burning rate will be about 3336-5560 g/a. Comparing the tritium generation with the consumption, the required TBR for tritium self-sufficiency should be higher.

| Parameters                        | Reasonable designed value | Baseline (variation) value of sensitivity analysis |
|-----------------------------------|---------------------------|-----------------------------------------------|
| Fusion power                      | 200 MW                    | 200 MW                                        |
| T burn-up fraction                | 1%                        | 0.5% (0.5%-2%)                                |
| T cycle time                      | 2-6 h                     | 6 h (2-6 h)                                   |
| Burning availability              | 30%-50%                   | 30% (30%-50%)                                 |
| Max. T retention in PFM           | 1 kg                      | 1 kg (1-4 kg)                                 |
| T retention in blanket            | Unknown (<2 kg)           | 2 kg                                          |
| T retention in tritium plant      | Unknown (<1 kg)           | 1 kg                                          |
| T nonradioactivity loss rate      | 40.6 g/a                  | 40.6 g/a                                      |

**Table 2** Baseline designed parameters of CFETR for tritium self-sufficiency evaluation
than 1.1 under the condition that the burning availability is 30%, the tritium burn-up fraction 1%, the tritium cycle time 6 hours and the tritium retention amount 4 kg.

To further discuss the required TBR variation interval, the sensitivity analysis was performed over tritium cycle time (2-6 hours), tritium burn-up fraction (0.5%-2%), tritium retention amount (1-4 kg), and burning availability (30%-50%) refer to Table 2. The results are shown in Figure 4. From the analysis, the required TBR of tritium self-sufficiency is in the interval of 1.07-1.13 based on CFETR design parameters. On the other hand, if some designed targets failed, for example, burning availability, which is a key issue for the future fusion reactors, the required TBR would be increased significantly. The required TBR would be higher than 1.3 if only achieving burning availability of 10%. Beyond the burning availability, the tritium retention would also be a significant parameter for tritium self-sufficiency. For the current condition, the tritium retention contributes most to the total inventory. The decay factor of tritium retention contributes most to the required TBR. Lots of previous studies also showed concerns about a possible quite tritium retention which would bring great challenges for both the tritium self-sufficiency and the personal safety.49-53 For CFETR, more R&D should be performed to validate tritium retention data and to develop new techniques with lower tritium permeation and retention in materials.

### 4.3 Achievable TBR of blankets

Three options of blankets have been designed for CFETR, including a helium gas cooled tritium breeding blanket, a water cooled blanket and a LiPb liquid metal coolant blanket.8 Tritium breeding is an important function of the blankets along with energy extraction and radiation shielding. Neutronics studies have been performed for three kinds of blankets. All calculations showed that the TBR would be about 1.1-1.2.54-57 Since these calculations do lack of detailed engineering modeling, for example, ignoring the ports effect, the calculated TBR would drop greatly if ports and heterogeneity effects would be considered in detail in 3-D engineering modeling. In our works, the TBR was estimated using neutronics modeling based on blanket design of CFETR. The models are shown in Figure 5 and are defined as 1-D sphere model, 2-D column model, simplified and complicated 3-D model, complicated 3-D model with different port numbers. The TBR results of DD and DT fusion neutrons are shown in Table 3. The results clearly show that the TBR decreases with the complexity of blanket models. If we keep 16 ports for the CFETR machine, the TBRDT would decrease to about 0.99. From this point, potential risk of achievable TBRDT < 1.0 cannot be eliminated. As for the real numbers of ports, these are not yet finalized for CFETR. Referred to ITER, about 44 ports (18 upper ports, 17 equatorial ports and nine lower ports) are needed for remote handling operations, diagnostic systems, heating and vacuum systems.46 Although there may be less ports for CFETR, it still may be the biggest challenge for the required TBR for tritium self-sufficiency.

Besides the determination of the TBR loss, there are also considerable uncertainties in the calculation results: due to the uncertainties of modeling, methods, and nuclear data, up to 10%-20% of maximum uncertainties exist in the calculations.13,47,58 Therefore, both considering the potential tritium loss and the uncertainties, the achievable TBR of a global blanket may be lower than the required TBR for tritium self-sufficiency. From this follows that the risk of failing tritium self-sufficiency of CFETR could not be eliminated.

### 4.4 Consequences in case of failing tritium self-sufficiency

There is no doubt that full power could be reached if tritium self-sufficiency is reached. However, according to the analysis above, the risk of failing the tritium self-sufficiency could not be eliminated. The consequences of failing tritium self-sufficiency were evaluated and are shown in Figure 6. CFETR could still achieve steady-state operation with a certain fusion power if failing tritium self-sufficiency. The direct effect is that the fusion power of steady state would be lower than the designed value. For the scenario of TBR = 1.08, the
steady-state fusion power would decrease a little compared to
the designed value. The fusion power is about 150-170 MW
for CFETR. For the scenario of TBR = 0.99, there will be a
large gap to tritium self-sufficiency and full fusion power.
The steady-state fusion power is about 33% of full power for
CFETR.

The fusion power loss corresponds to a benefit loss for
a fusion reactor compared with the tritium self-sufficiency
state. For phase I, the discussion of benefit loss is not so
important, as cost-benefit is not the foremost concern. But
for CFETR phase II with a fusion power over 1000 MW for
DEMO validation, the cost-benefit would be a more important
issue. For CFETR phase II, the cost-benefit evaluation for
full year operation was performed and is shown in Figure 7.
In case of failing tritium self-sufficiency, the costs of pur-
chasing tritium to keep full power and benefits loss of los-
ing energy are almost equivalent if the TBR is higher than
0.97. Below this value, costs of purchasing tritium to keep
full power operation would be more than the benefits loss of
the losing energy. Thus, if tritium self-sufficiency is failed,
it is more economical to do nothing than to purchase tritium
produced by CANDU reactors to compensate fusion power
to full power.

4.5 Future R&D needed for tritium self-sufficiency

According to the evaluation above, reaching the one coming
close to tritium self-sufficiency is necessary for an economic
fusion energy. There are still big challenges to achieve tritium
self-sufficiency, especially the uncertainties between simula-
tion and experimental results. In the future, more attentions
should be paid on the R&D issues, such as blanket TBR,
tritium burn-up fraction, tritium cycle time and retention in
materials during the engineering design phase of CFETR or
the next fusion reactors.

For the achievable TBR of blanket, firstly, the coverage
rate of ports should be as small as reasonably possible to
increase the global TBR as the ports are indispensable to
the fueling, heating and so on. Good design should avoid
the “buckets effect” for a whole fusion complex. Secondly,
the 3D neutronics model should be upgraded from existing
~10^3 cells to ~ 10^5 cells level, which could significantly
control the uncertainties of achievable TBR. And, essential
experimental validations with DT neutron source should
be performed to decrease the uncertainties in neutronics
database, for example, tritium breeding experiments under
module scale and fusion neutron environment.

Regarding the required TBR, the following related to pa-
rameters should be paid more attention:
1. Tritium burn-up fraction. A method should be found to increase the tritium pellet penetration depth to reach a longer tritium ion confinement time. Besides, simulation and validations should also be performed for the feasibility of: a) 50:50 DT mixed fueling for replenishing the burnt tritium and particle transport loss; b) pure D or others fueling for other requirements, for example, triggering the ELM frequency to reduce ELM energy loss, controlling the peak power load on the divertor plates.

2. Tritium cycle time. From design point of view, a detailed processing model should be developed based on an advance computation platform, for example, ECOSIMPRO. From engineering point of view, novel tritium cycle concepts and technology should be explored to increase the tritium cycle efficiency, for example, by combining the tritium process with fuel exhausting and quick refueling techniques. From demonstration point of view, a steady tritium process system with the ability of operation of 100-1000 g hydrogen considering the operation scenario of CFETR should be realized;

3. Tritium retention in materials. From simulation point of view, multiphysics and multiscales tritium transport simulation should be performed to investigate the effect of impurity deposition on the retention. From engineering point of view, high effective tritium removal techniques like ion-assisted cleaning methods (glow discharge cleaning, ion-cyclotron wall conditioning) should be explored on-line and the effect of regular cleaning cycles on the overall retention rates throughout different phases of CFETR operations should be evaluated. With regard to materials development, novel materials should be developed to control tritium retention and to quickly release tritium during baking, robust coating techniques should be found to prevent tritium permeation for CFETR scale.

To fill the gaps for CFETR tritium self-sufficiency, in reality, R&D works related with tritium self-sufficiency were deployed and are ongoing with the support by the Ministry of Science and Technology (MOST) of China. An overview of R&D including the scopes of blanket, tritium plant, materials (tritium retention),

**FIGURE 6** Ion density variation and fusion power loss in case of failing tritium self-sufficiency. A, Losing 1:1 of DT ion density ratio; B, Dynamic fusion power decrease and reach steady-state power at last; C, Steady-state fusion power vs blanket Tritium Breeding Ratio

**FIGURE 7** Cost comparisons of direct loss power and purchase tritium to reach full power for CFETR phase II in case of failing tritium self-sufficiency.
and plasma (tritium burn-up fraction) is shown in Figure 8. In the early years, most of the attentions were paid to the ITER TBM. Since 2011, the general design group for magnetic confinement fusion reactor was founded, which is also the original CFETR project team. Several projects were approved to support the concept design of CFETR. Eyes were also focused to the blanket design and tritium breeding experiment. Since December 2017, a new series of research projects were approved by Chinese government to start the engineering design of CFETR. At this stage, more attentions have been paid to tritium plant, materials and tritium burn-up fraction in addition to blanket. These researches aimed to balance the achievable global TBR of blanket with the required TBR for tritium self-sufficiency. It is self-evident Chinese government would make a stable budget support to fill the gaps for tritium self-sufficiency of CFETR. And it has long since been the holy grail of the fusion reactor to produce energy with economical fuels input.

5 | CONCLUSIONS

Tritium resources for the reactor start-up and tritium self-sufficiency during the operation is a key issue for CFETR. From this work, we make the following conclusions.

1. The tritium start-up amount for CFETR phase I is about 500-1500 g which mainly depends on the tritium burn-up fraction and tritium cycle time. The reasonable value of tritium burn-up fraction and tritium cycle time are 1% and 2-6 hours, respectively.

2. DD start-up seems to be a more feasible choice than to purchase kilograms of tritium from market for CFETR start-up, since the available commercial tritium resources are too scarce to fully supply fusion reactors after ITER consumption, for example, CFETR, EU-DEMO, K-DEMO, FNSF, and Japanese DEMO.

3. The blanket achievable TBR should be higher than 1.1 (evaluation result) of required TBR for tritium self-sufficiency of CFETR phase I. Risk of failing tritium self-sufficiency still cannot be eliminated according to the calculation results due to the inevitable tritium ports loss and the considerable calculation uncertainties.

4. In case of failing tritium self-sufficiency of CFETR, the consequences are the loss of fusion power. Taking TBR = 0.99 as an example, the steady-state achievable fusion power is about 33% of full power. It is more economic competitiveness to do nothing than purchase tritium to compensate fusion power to full power. Totally, it still could be acceptable even if slightly failing tritium self-sufficiency for CFETR.

ACKNOWLEDGMENTS

This work is supported by the China Postdoctoral Science Foundation (Grant No. 2018M640856), the National Natural

| Year | Project Title |
|------|---------------|
| 2009 | Solid and liquid TBM design & tech. (2009GB10800; 2009GB10900) |
| 2010 | Design of the tritium systems for China TBM and R&D on the key components tech. (2010GB112000) |
| 2011 | TBM irradiation experiment for tritium production rate (2010GB113000) |
| 2012 | Key Sci&Tech. of TBM and CFETR blanket (2013GB108000) |
| 2013 | Irradiation experiment of CFETR solid blanket (2014GB111000) |
| 2014 | Blanket design with high TBR for fusion reactor (2015GB110800) |
| 2015 | Concept design of tritium plant (2015GB111000) |
| 2016 | Tritium cycle tech. of blanket (2015GB110900) |
| 2017 | Overall design technology of CFETR tritium plant system (2017YF0390300) |
| 2018 | Tritium recovery and recycling technology for plasma exhaust gas of CFETR (SQ2017YF039085) |
| 2019 | Tritium extraction and measurement engineering technology for breeding blanket of CFETR (SQ2017YF039203) |
| 2020 | PFM tritium retention experiment for CFETR (SQ2017YF039010) |
| 2021 | Key tech. & assessment of tritium permeation barrier in 2017YF03005000 |

FIGURE 8: R&D work related with tritium self-sufficiency were deployed and are ongoing with the support by the Ministry of Science and Technology (MOST) of China.
Science Foundation of China (Grant No. 11505218), and the National Key R&D Program of China (Grant No. 2017YFE0300300).

**ORCID**

Muyi Ni http://orcid.org/0000-0003-0171-0277

**REFERENCES**

1. Lu L, Zhou L, Zhang H, Weng Y. The effects of industrial energy consumption on energy-related carbon emissions at national and provincial levels in China. *Energy Sci Eng*. 2018;6:371-384.

2. Lazarou S, Vita V, Diamantaki M, et al. A simulated roadmap of hydrogen technology contribution to climate change mitigation based on representative concentration pathways considerations. *Energy Sci Eng*. 2018;6:116-125.

3. Siemer D. Why the molten salt fast reactor (MSFR) is the “best” Gen IV reactor. *Energy Sci Eng*. 2015;3:83-97.

4. Wang J, Yang S, Jiang C, Zhang Y, Lund P. Status and future strategies for concentrating solar power in China. *Energy Sci Eng*. 2017;5:100-109.

5. Ongena J, Koch R, Wolf R, Zohm H. Magnetic-confinement fusion. *Nat Phys*. 2016;12:398-410.

6. Sanchez J. Nuclear fusion as a massive, clean, and inexhaustible energy source for the second half of the century: brief history, status, and perspective. *Energy Sci Eng*. 2014;2:165-176.

7. Bigot B. ITER: a unique international collaboration to harness the power of the stars. *CR Phys*. 2017;18:367-371.

8. Wan Y, Li J, Liu Y, et al. Overview of the present progress and future plans of pulsed fusion reactor. *J Fusion Energy*. 2017;118:5-10.

9. Wang X, Ran G, Wang H, Xiao C, Zhang G, Chen C. Current progress of tritium fuel cycle technology for CFETR. *J Fusion Energy*. 2019;38:125-137.

10. Chen H, Pan L, Lv Z, Li W, Zeng Q. Tritium fuel cycle modeling and tritium breeding analysis for CFETR. *Fusion Eng Des*. 2016;106:17-20.

11. Pan L, Chen H, Zeng Q. Sensitivity analysis of tritium breeding ratio and startup inventory for CFETR. *Fusion Eng Des*. 2016;112:311-316.

12. Wang X, Ran G, Wang H, Xiao C, Zhang G, Chen C. Current progress of tritium fuel cycle technology for CFETR. *J Fusion Energy*. 2019;38:616-620.

13. Glugla M, Antipenkov A, Beloglazov S, et al. The ITER tritium systems. *Fusion Eng Des*. 2007;82:472-487.

14. Taylor N, Parks P, Jernigan T, et al. Pellet fuelling and control of burning plasma in ITER. *Nucl Fusion*. 2007;47:443-448.

15. Foster D. Reorganizing algebraic thinking: an introduction to dynamic system modeling. *Math Enthusiast*. 2017;14:347-370.

16. Kasada R, Kwon S, Konishi S, Sakamoto Y, Yamashita T, Tobita K. A system dynamics model for stock and flow of tritium in fusion power plant. *Fusion Eng Des*. 2015;98–99:1804-1807.

17. Zhu Z, Nie B, Chen D. A system dynamics model for tritium cycle of pulsed fusion reactor. *Fusion Eng Des*. 2017;118:5-10.

18. Wong C, Merrill B. Use of system code to estimate equilibrium tritium inventory in fusion DT machines, such as ARIES-AT and components testing facilities. *Fusion Eng Des*. 2014;89:1482-1485.

19. Loarte A, Campbell D. The plasma physics aspects of the tritium burn fraction and the prediction for ITER. 4th IAEA DEMO Programme Workshop, November 15th-18th, 2016, Karlsruhe, Germany.

20. Kukushkin A, Polevoi A, Pacher H, Pacher G, Pitts R. Physics requirements on fuel throughput in ITER. *J Nucl Mater*. 2011;415:S497-S500.

21. Abdou M, Vold E, Gung C, Youssef M, Shin K. Deuterium-tritium fuel self-sufficiency in fusion reactors. *Fusion Technol*. 1986;9:250-285.

22. Anderson J, Bartlit J, Carlson R, et al. Experience of TSTA milestone runs with 100 grams-level of tritium. *Fusion Technol*. 1988;14:438-443.

23. Zheng S, King D, Garzotti L, Surrey E, Todd T. Fusion reactor start-up without an external tritium source. *Fusion Eng Des*. 2016;103:13-20.

24. Cristescu IR, Cristescu I, Doerr E, Glugla M, Murdoch D. Tritium inventories and tritium safety design principles for the fuel cycle of ITER. *Nucl Fusion*. 2007;47:S458-S463.

25. Abdou M, Morley N, Smolentsev S, et al. Blanket/first wall challenges and required R&D on the pathway to DEMO. *Fusion Eng Des*. 2015;100:2-43.

26. Abdou M. Tritium fuel cycle, tritium inventories and physics and technology R&D challenges for: 1) enabling the startup of DEMO and future power plants and 2) attaining tritium self-sufficiency in fusion reactors. 13th International Symposium on Fusion Nuclear Technology (ISFNT-13), September 25th-29th, 2017, Kyoto, Japan.

27. Carella E, Moreno C, Urgorri F, Rapisarda D, Ibarra A. Tritium modelling in HCPB breeder blanket at a system level. *Fusion Eng Des*. 2017;124:687-691.

28. Ying A, Zhang H, Merrill B, Ahn M, Cho S. Breeding blanket system design implications on tritium transport and permeation with
high tritium ion implantation: a MATLAB/Simulink, COMSOL integrated dynamic tritium transport model for HCCR TBS. *Fusion Eng Des.* 2018;136:1153-1160.

40. Konishi S, Asaoka Y, Hiwatari R, Okano K. Possible scenario to start up DT fusion plant without initial loading of tritium. *J Plasma Fusion Res.* 2000;76:1309-1312.

41. Konishi S, Kasada R, Okino F. Myth of initial loading tritium for DEMO-Modelling of fuel system and operation scenario. *Fusion Eng Des.* 2017;121:111-116.

42. Chan V, Costley A, Wan B, Garofalo A, Leuer J. Evaluation of CFETR as a fusion nuclear science facility using multiple system codes. *Nucl Fusion.* 2015;55:023017.

43. Wan B, Ding S, Qian J, Li G, Xiao B, Xu G. Physics design of CFETR: determination of the device engineering parameters. *IEEE Trans Plasma Sci.* 2014;42:495-502.

44. Ma J. On-grid electricity tariffs in China: development, reform and prospects. *Energy Pol.* 2011;39:2633-2645.

45. Roth J, Tsitrone E, Loarte A, et al. Recent analysis of key plasma wall interactions issues for ITER. *J Nucl Mater.* 2009;390-391:1-9.

46. ITER Organization. *Preliminary Safety Report, (Rapport Préliminaire de Sûreté, RPPrS), ITER_D_3ZR2NC v3.0.*

47. El-Guebaly L, Malang S. Toward the ultimate goal of tritium self-sufficiency: technical issues and requirements imposed on ARIES advanced power plants. *Fusion Eng Des.* 2009;84:2072-2083.

48. Rosanvallon S, Torcy D, Chon J, Dammann A. Waste management plans for ITER. *Fusion Eng Des.* 2016;109-111:1442-1446.

49. Counsell G, Coad P, Grisola C, et al. Tritium retention in next step devices and the requirements for mitigation and removal techniques. *Plasma Phys Controlled Fusion.* 2006;48:B189-B199.

50. Wang Z, Chen C, Song Y, et al. Deuterium retention removal in China reduced activation ferritic-martensitic steels through thermal desorption and hydrogen isotope exchange. *Fusion Eng Des.* 2018;126:139-146.

51. Nie B, Ni M, Wei S. Individual dose due to radioactivity accidental release from fusion reactor. *J Hazard Mater.* 2017;327:135-143.

52. Nie B, Ni M, Liu J, Zhu Z, Zhu ZL, Li F. Insights into potential consequences of fusion hypothetical accident, lessons learnt from the former fission accidents. *Environ Pollut.* 2019;245:921-931.

53. Nie B, Ni M, Jiang J, Wu Y. Dynamic evaluation of environmental impact due to tritium accidental release from the fusion reactor. *J Environ Radioact.* 2015;148:137-140.

54. Li Z, Feng K, Zhao Z, Zhao F, Feng Y, Xu K. Neutronics study on HCCB blanket for CFETR. *Fusion Eng Des.* 2017;124:1273-1276.

55. Liu S, Ma X, Jiang K, et al. Conceptual design of the water cooled ceramic breeder blanket for CFETR based on pressurized water cooled reactor technology. *Fusion Eng Des.* 2017;124:865-870.

56. Ni M, Lian C, Zhang S, Nie B, Jiang J, Team FDS. Structural design and preliminary analysis of liquid lead-lithium blanket for China fusion engineering test reactor. *Fusion Eng Des.* 2015;94:61-66.

57. Cui S, Zhang D, Lian Q, et al. Evaluation and optimization of tritium breeding, shielding and nuclear heating performances of the helium cooled solid breeder blanket for CFETR. *Int J Hydrogen Energy.* 2017;42:24263-24277.

58. Fischer U, Bachmann C, Palermo I, Pereslavtsev P, Villari R. Neutronics requirements for a DEMO fusion power plant. *Fusion Eng Des.* 2015;98-99:2134-2137.

---

**How to cite this article:** Nie B, Ran G, Zeng Q, et al. Insights into fuel start-up and self-sufficiency for fusion energy: The case of CFETR. *Energy Sci Eng.* 2019;7:457-468. [https://doi.org/10.1002/ese3.291](https://doi.org/10.1002/ese3.291)