

Research Article

Preliminary Study on Risk Identification and Assessment Framework for Fusion Radioactive Waste Management

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Fusion reactors are expected to be safer, more environmentally friendly, and to have a lower nuclear proliferation risk, compared with other nuclear energy systems. However, it is widely recognized that a large amount of radioactive materials will be produced by a fusion reactor. Therefore, it is important to fully understand the overall radiation risk level of fusion radioactive wastes (radwaste) compared with existing nuclear energy systems. Studies on the treatment of the fusion radwaste have been currently focused on three ultimate options: clearance, recycling, and disposal by activation assessment of radioactive materials from the operation and decommissioning of fusion reactors. However, the radiation risk in the management of fusion radwaste, especially in the final disposal, was seldom studied. Based on the comparative analysis of fusion radioactive waste with ITER and fission reactors (e.g., pressurized water reactor, PWR), this paper tries to discuss how to determine the radiation risk in the process of fusion radwaste management on the premise of the current feasible industrial technology. On this basis, a risk assessment framework for repository disposal under normal degradation and external events is proposed.

1. Introduction

The production of radioactive materials has been regarded as an important issue in the development of fusion energy since 1970s [1]. Since the late 1990s, some international research projects have been carried out [2], focusing on the analysis of three scenarios in the management of fusion radioactive materials: clearance, recycling, and disposal. More recently, a new strategy has been promoted: avoiding underground disposal as much as possible, maximizing the reuse of activated radioactive materials through clearance, and recycling [3].

According to the definition of risk, i.e., “set of three triplets” [4], the risk assessment framework of fusion radwaste in a repository can be defined as the method for studying (1) what may happen, (2) how likely it is, and (3)

what the consequences are. The first triplet mainly refers to the behavior leading to radioactive release or radiation exposure. There has been a lot of research in this field, including the neutronics analysis and waste classification for different kinds of tokamak and their in-vessel components designs. The studies of fusion radwaste are mainly confined to the activation assessment of radioactive materials during operation and after decommissioning, and the management proposals on the classifications of radwaste are given according to the criteria. For the second triplet, “how likely” means the probability of the behavior. But few research studies on this topic has been done for fusion waste disposal. Therefore, there is still a lack of understanding of the radiation risk during final disposal in the repository. Moreover, some recommended criteria used in the application of recycling and

clearance [5–8] are based on the assumption that those advanced remote handling and processing technologies can be industrialized. However, the necessity to understand the radiation risk of fusion radwaste should not be glossed over, due to the great gaps between the assumption and current industrial technologies. This requires an assessment of the risk for the potential release of radioactivity in a long burial time.

By comparing with ITER and fission reactors (e.g., PWR), this paper introduces the characteristics of fusion radioactive waste and identifies the radiation risk existed in the process of fusion radwaste management. On this basis, this paper proposes a risk assessment framework for disposal in repository under normal degradation and external events. The structure of this paper is as follows. Section 2 introduces the characteristics of fusion radioactive waste in comparison with ITER and PWR. Section 3 gives the radiation risk identified in the management procedures of fusion radwaste. Section 4 presents the risk assessment framework for fusion radwaste disposal in repository. Finally, Section 5 gives conclusions of this study.

2. Characteristics of Fusion Radioactive Materials

Compared with PWR nuclear radwaste, fusion radwaste has its unique and significant characteristics. First, a large amount of radioactive material will be generated during the operation life of a fusion reactor. Taking ITER, a fusion experiment reactor, as an example, it is estimated that the operational wastes are roughly about 4,500 metric tons, and the dismantling wastes are approximately nearly 34,000 metric tons (excluding buildings) [9]. Due to the higher neutron flux, the 1 GWe fusion reactor can produce $5 \times 10^4 \sim 12 \times 10^4$ metric tons waste [10], which is much higher than those of a PWR of similar nuclear power (about 5000 metric tons [11]).

Second, since there are no transuranic nuclides and long-lived fission products in fusion, the radioactive inventory can be reduced by selecting appropriate materials. Most of the radioactive materials, generated during fusion reactor operation and decommissioning, are activated solid metallic materials from the tokamak components (e.g., blanket, divertor, shield, vacuum vessel, and magnets) and concrete from the bioshield. In addition, the tritium is a radioactive substance with strong permeability, which exists in nearly 90% active substances in fusion reactors. Many components of the tritium cycle system in the tritium plant are also treated with tritium, but there is no neutron radiation (called pure tritiated waste), in which tritium content is as high as 10^9 Bq/kg [12]. These characteristics lead to complexity in the radwaste management.

Third, during the cooling time of one day, the total decay heat density of fusion in-vessel components is about 10 W/kg, which is still far lower than that of a fission reactor core (~ 300 W/kg) [13]. However, the activity of highly activated blankets and divertors of fusion reactors is about $10^8 \sim 10^9$ GBq/m³ [14], which is even higher than the value of the IAEA limit [15] for the classification of high-level waste (HLW). In most countries, even within 100 years of cooling down, most parts of the blankets and divertors of a fusion

reactor would be ILW [16, 17], and fusion may produce more LLW than fission [18]. Actually, the total radioactivity of radioactive materials would be 10^{11} GBq, which is consistent with the magnitude of PWR. For the biological hazard potential (BHP), that is, the potential radioactive risk to the environment and human beings, measured by the amount of water used to dilute radionuclides to an acceptable level in drinking water, a fusion reactor is smaller than that of a PWR (Figure 1).

3. Radiation Risk during Fusion Radioactive Materials Management

3.1. Management Procedures of Radioactive Materials. According to the fusion radwaste management procedures recommended by ITER [21] and DEMO [12], as well as the characteristics of fusion radioactive waste, this paper proposes the decision tree for management procedures shown in Figure 2. After tokamak shutdown for replacement or decommissioning, the removed activated components are first preprocessed in the tokamak plant, including cooling, cleanup, and replacement. Then, the following treating measures are determined based on radioactivity. Actually, in order to determine whether further treatment is needed and what techniques should be adopted [22], the physical, chemical, and radiological behaviors of radioactive substances should be characterized and analyzed throughout the whole management process. Detritiation can also be taken in this period, as well as during temporary storage of plasma-facing components and tritium breeding units, considering activity limitations on tritium in different national repositories [16]. Temporary storage is required for 50~100 years until the acceptable criteria is satisfied [12]. Decarburization would also be needed to reduce the activity of ¹⁴C in the ILW [23].

If the radioactive materials meet the clearance or recycling criteria, they can be disposed or recycled as non-radioactive waste. Radioactive materials that cannot meet the criteria and are no longer expected to be used are usually conditioned in a hot cell or radwaste facility building. After decades of destruction and temporary storage, the radioactive waste which is still highly activated will be sealed up in containers, transported, and disposed of in the low and intermediate level waste repositories (LILW).

Clearance index (CI) is used to evaluate whether radioactive material meet the clearance criteria [24]. The clearance criteria are derived based on annual individual effective dose of $10 \mu\text{Sv}$ and vary from country to country. Our evaluation shows that less than 10% volume of radwaste from the commissioned reactor can meet the clearance criteria within 100 years of storage, including biological shield (about 1 year) and cryostat (70 years [25] or so). Large amounts of slightly contaminated housekeeping (including some tritiated waste) from fusion reactor operation can also be cleared.

As to metallic material with severe radiation damage and complex structures, it needs detritiation and melting before recycling. According to the statement of IAEA [26], 2 mSv/h is now the maximum allowable contact dose rate for workers in the industrial process of melting radioactive material. Our evaluation shows that 80% volume of fusion reactor radwaste

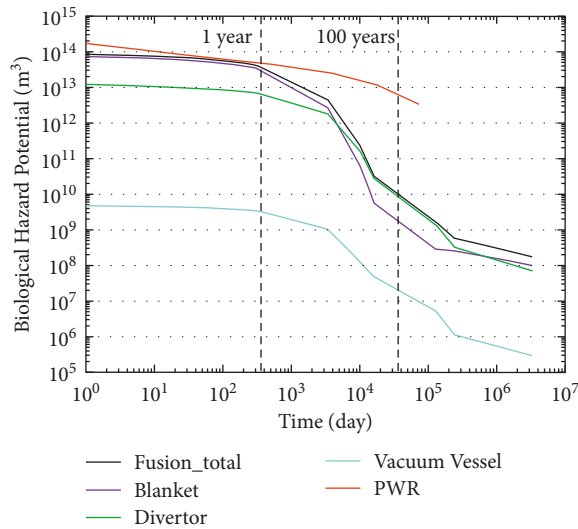


FIGURE 1: BHPs of fusion in-vessel components, including component replacement. This fusion reactor has an installed capacity of 1 GWe and PbLi breeding blankets design [10]. The irradiation duration for blankets and divertors are 5 years and 2.5 years, respectively. The duty time of the VV is the entire plant life. The radionuclide inventory after 30 years of operation is calculated by neutronics code SuperMC [19] and FENDL3.1 data library [20], and BHP is obtained by dividing the inventory for each nuclide by its maximum permissible concentration in water. The tritium contribution to BHP has been removed, considering the detritiation process in the fusion radwaste treatment. For the PWR, the weight of spent fuel is approximately 30 tons and refueling is carried out every 1.5 years.

can be recycled within 100 years of storage. To recycle more fusion radwaste and shorten the storage time, more advanced remote handling technology should be developed in the melting and reutilization process, which would pose a great challenge. Based on the current and foreseeable technologies, the amount of radwaste from fusion reactors to be disposal of would greatly exceed our assessment (10%).

3.2. Risk Identification in Radwaste Management. Under the nuclear waste classification regulations in many countries, the LLW of fusion requires surface burial, while the ILW requires long-term subsurface disposal. Occupational irradiation exposure is hard to be avoided in the radwaste management procedure of fusion reactors as mentioned above, even though workers may be equipped with remote handling and radiation protecting facilities. Some unexpected events may also bring additional radiation risk, such as sudden falls of equipment during the hoisting period, spraying radioactive dust, or rupture of buckets containing radioactive material during transportation [27].

4. Risk Assessment Framework for Fusion Radwaste Disposal

Societal risk can also be created in the long-term disposal considering the release of radioactive material after the degradation of the confined barrier, and radionuclides permeating

into water and release into biosphere. In the long-term post-closure phase, the disposal facilities may be damaged by many kinds of external events. Due to the confinement failure caused by external events such as drilling intrusion, radionuclides could be directly released into the environment, which may cause adverse effects on human health and may cause panic. From the viewpoints of risk perception [28], it is very important to evaluate potential radiation risk generated by the disposal of fusion radwaste. The quantitative assessment of consequences doses for the scenarios is performed using mathematical models that are derived from the conceptual models [29]. The essential elements for evaluating radiological dose to human include the following [30]:

- (a) Description of the repository site and the engineered systems.
- (b) Identification of events that may affect the long-term facility performance.
- (c) Description of control processes that affect the movement of radionuclides from LILW repository units to the general environment.
- (d) Computational calculation of doses to members of the general public.
- (e) Evaluation of the uncertainties in the computational results.

4.1. Normal Degradation Release. Development of a source term model incorporating fusion radwaste disposal facility should consider the forms and types of waste in the disposed inventory, as well as the release mechanisms according to the characteristics of the disposal site and the engineered barriers [31]. The structure of fusion LILW repository should include natural barriers (such as soil and rocks) and engineered barriers (such as top cover, isolation, and backfill). According to the requirement of IAEA's near surface disposal site [22, 31], a conceptual design of LILW repository for fusion radwaste disposal is provided, as shown in Figure 3. Engineered barriers are usually designed to isolate waste and prevent water from contacting waste, limit the release of radionuclides from disposal units to the environment, and reduce the doses to potential human intruders.

In the quantitative analysis of source term, the time history of artificial barriers' failure is assumed, such as drum failure 100 years after closure, concrete cubes failure 300 years after closure and cover failure 500 years after closure [31]. The radwaste mainly comes from highly activated metal and secondary radwaste, and the main radionuclides after hundreds of years of disposal would be ^{14}C , ^3H , ^{94}Nb , ^{63}Ni , etc. ^{94}Nb and ^{63}Ni could be released in the liquid form, and the KIM model [31] can be adopted to evaluate the release of radionuclides from the repository and their migration through the unsaturated zone. ^3H and ^{14}C could be released in a gaseous form [32], and can be performed considering a conservative conceptual model, in which the whole volatile radionuclide inventory in the repository is assumed to be available for mobilizable, and a one-dimensional diffusion model can be used for transportation calculation [29].

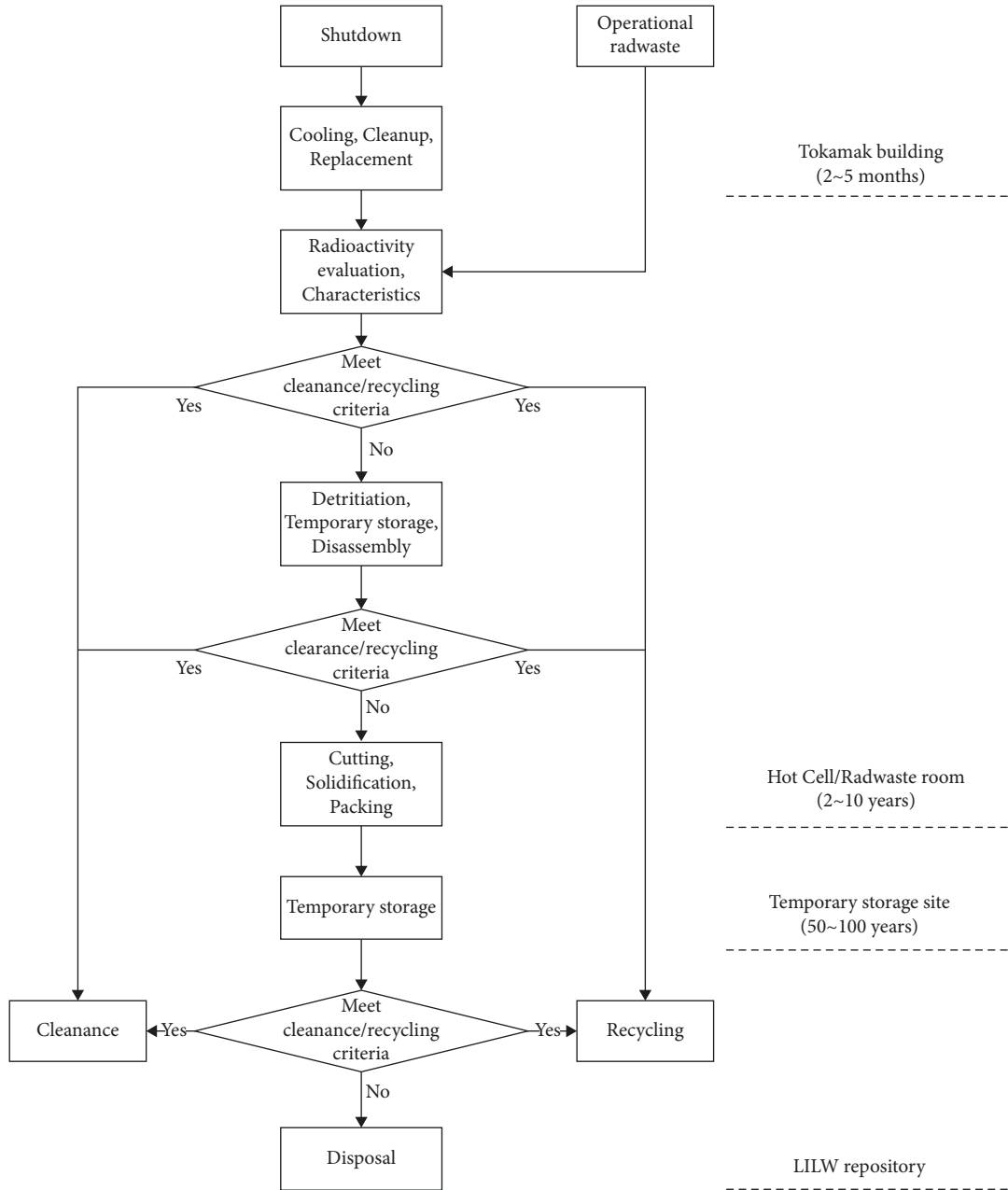


FIGURE 2: Managing procedures for fusion radioactive materials.

After releasing from the disposal facility, the radionuclides are transported in the geosphere and biosphere. Simplified terms over very large spatial and temporal scales can be used to develop the models of radionuclide transport, and the sensitivity and uncertainty analyses are also required. As the normal degradation of nuclear waste requires a long-term scale, the compartmental modeling can be used [33], in which the environment is partitioned into a finite number of compartments, while each compartment is considered to be fully mixed. Transfers between compartments follow first-order kinetics. A general n -compartment model system can be completely described by a set of n equations in the following form:

$$\frac{dq_i}{dt} = \sum_{j=1}^n \lambda_{ji} q_j - \sum_{i=1}^n \lambda_{ij} q_j - \lambda_i^L q_i + I_i(t), \quad (1)$$

where q_i represents radionuclide content of the compartment i ; λ_{ji} is the constant rate releasing from compartment j to compartment i (note that λ_{ji} is not defined for $i \neq j$); λ_i^L is the constant rate of releasing from compartment i to outside (including radioactive decay and external sink as a consequence of radioactive decay); and $I_i(t)$ is the rate of radionuclide input into compartment i from outside at time t (this could be the result of physical transfer of the radionuclide from outside, as well as the radioactive decay of its parent within the system).

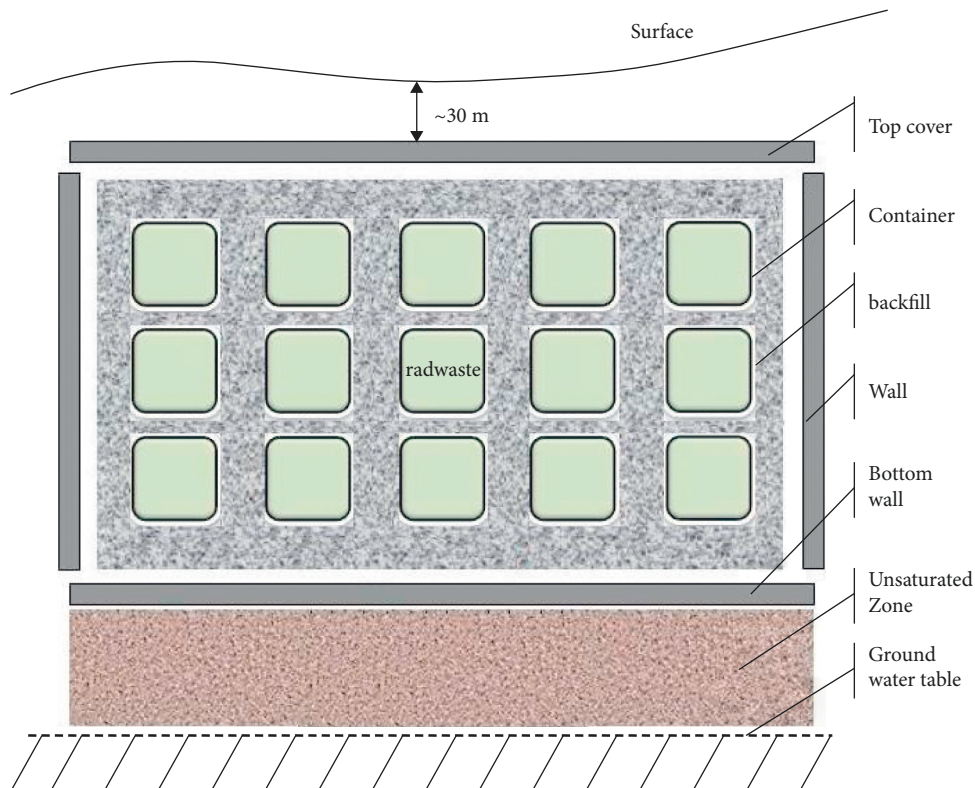


FIGURE 3: Conceptual design of LILW repository for fusion radwaste.

Aquatic and terrestrial ecosystems are considered separately for the behavior of various radionuclides in biosphere [33]. The surface water and groundwater are the main media for radionuclides entering the aquatic ecosystems. Soils and plants may be contaminated by the radionuclides released into aquatic systems. Radionuclides could also enter the terrestrial environment due to their release into the soils, or dry and wet deposition on soils and vegetation. The equilibrium models will be used for assessment, where the concentration of a radionuclide in one component of the ecosystems is derived assuming a direct correlation with another component of the ecosystems [33]. Generally, this relationship is considered proportionate. For example, the concentration of radionuclides in plants is set to be proportional to their concentrations in soil, and the constant of proportionality is called the soil-plant transfer factor [34]. As for tritium and ^{14}C from the fusion radwaste, this transfer factor would be equal to 1. For the distribution and migration of radionuclides under the scale of a surface-water catchment, the expanded SHETRAN model [35–38] and the MIKE-SHE model [39] are recommended [33].

The dose to human includes external exposure due to the radionuclides in the plume or deposited on the ground, or from the contaminated water body, as well as internal dose from inhalation and ingestion of polluted water or food. These factors have to be considered comprehensively. Sophisticated radiation transport codes would be required to calculate the effective dose rates resulted from external exposure. This takes into account the characteristics of pollution source and environmental, as well as the exposed

individual. However, precomputed effective dose rates per unit concentration can also be used. As for computing effective doses from inhalation, a human respiratory tract model is recommended [40].

4.2. External Event Release. Deterministic or probabilistic methods can be applied to evaluate the risk caused by a single external event [41]. However, for the societal risk from all kinds of external events, due to the great uncertainty of scenarios and complexity of their combinations as well as the possible probability limitations in the regulation acceptance criteria, it is recommended to adopt the probabilistic approach by combining with the deterministic evaluation for the human doses, such as the EPA requirements for the disposal of radioactive waste [42]. There have been some research studies on the external event assessments of the disposal of fission radioactive wastes, and this paper attempts to deduce its quantitative risk assessment methods according to the characteristics of fusion radwaste repository.

Risk assessment of external events shall include the following five aspects: event scenario identification, scenario probabilities' development, source term analysis, radiation dose assessment, and result verification.

4.2.1. Event Scenario Identification. There are generally two kinds of scenarios in fusion radwaste repository: inadvertent human intrusion, and earthquake. Other events can also be considered, such as volcanic activities or malicious attacks. Compared with fission radionuclides, fusion radionuclides

have shorter half-life and therefore have less impact on long-term natural processes. On the basis of local history statistics, population distribution, human activities, and future development plans, “top-down” method, such as the Rock Engineering System [43] or “bottom-up” method, such as the Process Influence Diagram [29, 33] can be adopted to analyze and group the external events, combined with expert judgments, and to select the representative events according to the assessment purpose. The external events categories and scenarios are listed in Table 1. Considering the depth of near surface disposal of fusion radwaste, inadvertent human intrusion may bring great risks to fusion disposal facilities. Therefore, drilling intrusion will be taken as an example to explain the probabilistic assessment of external event scenarios for fusion radwaste disposal facilities.

4.2.2. Scenario Probabilities' Development. Data related to drilling specific scenario, such as occurrence time, location, and the impact on repository, is generally uncertain and hard to predict. Therefore, the form of vectors is used to categorize the scenarios and develop their probabilities. To simplify the analysis, suppose that the scenarios occur independently in time and space [44], which is described by the Poisson distribution, as shown in equation (2). Other distributions can also be used to describe, such as exponential or uniform distribution, according to the information collected in repository site. The parameters of these distributions need to be determined according to the repository design, site population, environments, etc., combined with expert judgments. Then, data for scenarios can be generated from these distributions by sampling methods such as Monte Carlo, Latin Hypercube, etc.

$$S_m = 1 - e^{-\lambda m},$$

$$t = \frac{\ln(1 - \varepsilon)}{\lambda}. \quad (2)$$

Among the equation, S_m is the cumulative probability distribution function of m , m is the occurrence time of the scenario, ε is the random number between 0 and 1 generated by sampling, and λ is the average occurrence rate of the scenario (1/year). The value of λ is suggested to be 3.28×10^{-4} /year by references [42, 45] for the assessment of fission repository. Although the repository types have a great impact on the degree of breach for external events, they have little impact on the occurrence time of events. Thus, this value can also be applied to fusion disposal facility.

Take drilling for an example, the elements $X_d = \{T_i, L_i, D_i, N_i, P_i\}$ of the sample space are in the form of vector. In which, T_i represents the time of the i th drilling, L_i is the location of the i th drilling (distance to repository), D_i represents the depth and diameter of a drilling intrusion, N_i is the type of waste released by the i th drilling (i.e., nuclides and amounts in the waste), and P_i designates the remediation procedure after the i th intrusion. It is worth noting that criteria should be developed to determine how the scenarios will affect the repository. Then, each element of X_d need to be categorized and sampled according to the features of the evaluated fusion disposal facility. For example, since the

half-life of fusion waste radionuclides are shorter than those of fission, the occurrence time can be grouped by 100 years. Meanwhile, the depth of drilling can be categorized into two groups, one group is under 30 m, and the other group is over 30 m. A depth of 30 m can be used to distinguish between near surface disposal and intermediate depth and is treated as the normal residential intrusion depth [22]. Finally, the occurrence frequencies of each scenario group can be calculated based on the sampling data. The detailed calculating flowchart for the occurrence frequency of drilling is shown in Figure 4, where N_T , N_L , and N_D are the loop variables of drilling time, drilling location, depth and diameter of a drilling intrusion respectively. \hat{T}_i , \hat{L}_i , \hat{D}_i , \hat{N}_i , and \hat{P}_i are the simulated samples, in which \hat{N}_i , \hat{P}_i are used to evaluate the radiation doses. For conservative purpose, the maximum radiation dose in all the samples can be selected as the consequence of the drilling event. F_x^{-1} is the inverse function of random variable x , which can be obtained through historical data or experts judgement. ε_i is random variable generated by any standard random generator. Then, the occurrence frequency P_f of the scenario $X_d = \{X_d | T_i < T, L_i < L, D_i < D, N, P\}$ can be evaluated as: $P_f = P_L \times P_T \times P_D$.

4.2.3. Source Terms and Radiation Dose Assessment. Variation of the radionuclides in the fusion radwaste with time can be obtained by neutronics calculations. Based on the diffusion pattern of these radionuclides in the solidification material, the inventory of mobilizable radionuclides can be calculated and used as the source term of subsequent analysis. It is worth noting that although deuterated several times during radwaste processing, a relatively huge amount of tritium still remains in the material. Tritium in HTO and ^{14}C in CO_2 may be released in the form of gas or dissolved in water. In an intrusion event, radiation will do harm to human beings in many ways. The transport paths generally include underground water, soil, terrestrial animals, plants, groundwater, aquatic animals, and air. The deterministic dose can be assessed based on the repository design and surrounding environment discussed in Section 4, with reference to the assessment methods for fission reactor release waste, as shown in reference [46–48].

4.2.4. Result Verification. The effectiveness and sufficiency of the models, assumptions, and data need to be verified and modified if necessary. In addition, sensitivity and uncertainty analysis is required to present the results in an appropriate form. The complementary cumulative distribution function (CCDF)-based risk curve is recommended to present the societal risk of a fusion radwaste repository, due to the long-term threat of the external events. Risk is sometimes defined as probability multiplied by the consequence, but any single value is not enough to convey the concept of risk. The risk curve based on CCDF provides more complete information. The CCDF risk curve describes the cumulative frequencies of accidents exceeding given doses from the entire spectrum of accident sequences [49]. Hence, it is suitable for demonstrating the societal risk of fusion reactors. Detailed description of the CCDF-based method risk curve is shown in Figure 5.

TABLE 1: Typical external event scenarios.

External factor	Event category	Scenario
Human activity	Inadvertent human intrusion	Near surface: agriculture, stockbreeding, construction, etc. Intermediate depth: drilling, mining, archaeology, geothermal energy extraction, etc.
	Malicious intrusion	Terroristic attack, etc.
Natural process and event	Nonhuman intrusion Natural disaster	Animal intrusion, plant intrusion Earthquake, volcanic activity, glaciation, etc.

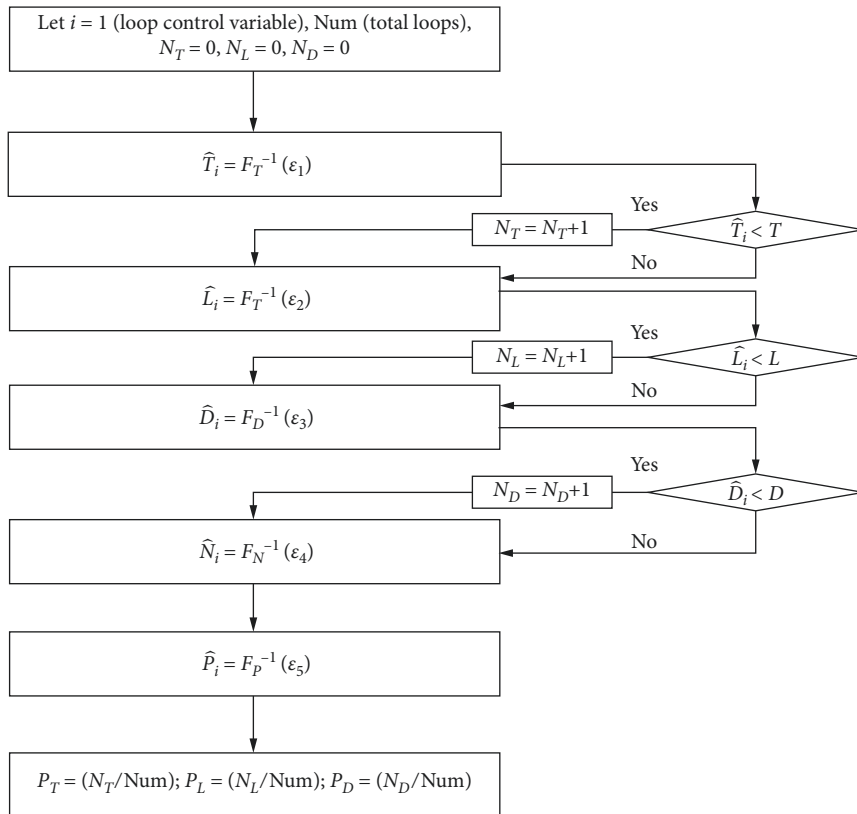


FIGURE 4: Flowchart for the occurrence frequency of drilling.

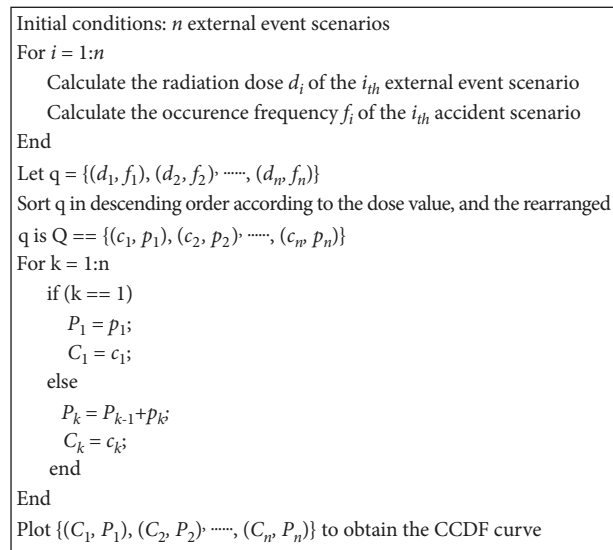


FIGURE 5: CCDF-based risk curve for a fusion radwaste repository.

5. Conclusions

In this paper, the characteristics of fusion radwaste are presented. Then, based on the currently proposed clearance/recycling strategy and feasible industrial technologies, the management procedure of fusion radioactive materials is proposed. Risks in the process of fusion radwaste management are identified, mainly from near surface and sub-surface disposal. The risk assessment framework of normal degradation release and external events in repository is presented, in which, a typical normal degradation release scenario is given and external event scenarios are identified and categorized. The complementary cumulative distribution function (CCDF)-based risk curve is recommended to present the societal risk of a fusion repository.

Abbreviations

BHP:	Biological hazard potential
CCDF:	Complementary cumulative distribution function
CI:	Clearance index
DEMO:	Demonstration reactor
EPA:	Environmental protection agency
HLW:	High-level waste
IAEA:	International atomic energy agency
ILW:	Intermediate level waste
ITER:	International thermonuclear experimental reactor
LILW:	Low and intermediate level waste
LLW:	Low level waste
PbLi:	Lead-lithium alloy
PWR:	Pressurized water reactor
F_x^{-1} :	Inverse function of random variable x
P_i :	Remediation procedure after the i th intrusion
q_i :	Radionuclide content of the compartment i
λ_{ji} :	Constant rate from compartment j to compartment i
λ_i^L :	Constant rate of releasing from compartment i to outside
I_i :	Rate of radionuclide input into compartment i from outside at time t
P_t :	Poisson distribution
S_m :	Cumulative probability distribution function of t
m :	Occurrence time of the scenario
ε :	Random numbers between 0 and 1 generated by sampling
λ :	Mean occurrence rate of the scenario (1/year)
X_d :	Drilling sample space are in the form of vector
T_i :	Time of the i th drilling
L_i :	Location of the i th drilling
D_i :	Depth and diameter of a drilling intrusion
N_i :	Type of waste released by the i th drilling.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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