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Individual dose due to radioactivity accidental release from fusion reactor

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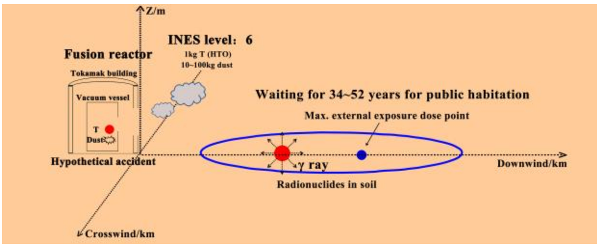
Graphical abstract



Highlights

- Conservative early dose of different unit fusion radioactivity release were assessed.
- Data of accident level in INES for fusion reactor were proposed.
- Method of environmental restoration time after fusion accident was proposed.
- The maximum possible accident level for fusion reactor is 6.
- We need 34~52 years to live after the fusion hypothetical accident.

Abstract: As an important index shaping the design of fusion safety system, evaluation of public radiation consequences have risen as a hot topic on the way to develop fusion energy. In this work, the comprehensive public early dose was evaluated due to unit gram tritium (HT/HTO), activated dust, activated corrosion products (ACPs) and activated gases accidental release from fusion reactor. Meanwhile, considering that we cannot completely eliminate the occurrence likelihood of multi-failure of vacuum vessel and tokamak building, we conservatively evaluated the public radiation consequences and environment restoration after the worst hypothetical accident preliminarily. The comparison results show early dose of different unit radioactivity release under different conditions. After further performing the radiation consequences, we find it possible that the hypothetical accident for fusion reactor would result in a level 6 accident according to INES, not appear level 7 like Chernobyl or Fukushima accidents. And from the point of environment restoration, we need at least

69 years for case 1 (1kg HTO and 1000kg dust release) and 34~52 years for case 2 (1kg HTO and 10kg~100kg dust release) to wait the contaminated zone drop below the general public safety limit (1mSv per year) before it is suitable for human habitation.

Key words: Tritium; Dust; Dose; Fusion reactor; Environment restoration

1. Introduction

Fusion concepts studies carried out in past years have shown favorable features of fusion [1-3]. Meanwhile, specific environmental issues are introduced due to large amounts of tritium cycle and neutron activation in a fusion reactor. In the ITER design, safety limit of 1kg tritium and 1000kg dust was set in the vacuum vessel (VV) [4]. Once the worst hypothetical accident happened in the ITER like fusion reactor, it is possible, although probability is very low, large amounts of radioactivity would release into environment and threaten public safety [5,6]. Thus, radiological consequence assessment has risen as one of the major issues in developing fusion energy.

Series assessment of public dose due to tritium release was carried out for ITER and fusion reactor [7-10]. Former evaluations mainly focused on the public dose due to tritium gas (HT) and tritiated water (HTO) release from ITER and fusion reactor [11], few attention was paid to the public dose due to activated dust (dust), activated corrosion products (ACPs)[7][12], and activated gases (^{41}Ar, $^{14}CO_2$) accidental release from fusion reactor. The transfer behavior of HT, HTO in the environment and human body is well understood, but not for dust, and activated gases [12]. Thus, in compliance with scientific justification, various radionuclides accidental release from fusion reactor should be took into detailed consideration.

To easily define nuclear accident consequences, the international nuclear and radiological event scale (INES) was developed in 1990 by international experts convened by the IAEA and the OECD nuclear energy agency (OECD/NEA) [13]. Accidents, happened in Chernobyl and Fukushima fission reactors, have been defined as level 7 (the worst accident case) according to INES. Here the question was proposed that which level of INES would happen once the most severe accident happened in fusion reactor.

After the hypothetical accident, related emergency measures must be taken to ensure public safety. The direct and effective way of avoiding the high radiation dose is to make the residents evacuate from contaminated area along downwind of the accidental nuclear reactor. Take Chernobyl accident for example, “exclusion zone” was set as a 30km radius (2800km^2) around the fission reactor. And there is still no residents living around the reactor after 30 years natural restoration because of the long-lived radionuclides released from fission reactor. As is well known, fusion reactor was publicized as none long-lived radionuclides in the reactor. Thus, it is an interesting issue to evaluate when we can live safely around the fusion reactor after the hypothetical accident.

On the basis of the public safety issues mentioned above, this study aims to perform the conservative public radiation consequences assessment on the point of public radiation dose, INES level and environment restoration time after the hypothetical accident although it is a very low probability accident, in which both the two safety confinements (vacuum vessel and tokamak building) fail to work. Just like our understanding on Fukushima accident, we always held that the containment building of fission reactor could not be destroyed before Fukushima accident happened. However, the low probability accident happened and developed as an INES 7 accident at last.

2. Material and methods

2.1. Potential radioactive source

Radioactive gaseous effluents mainly consist of the following according to ITER safety approach for our reference: HTO, HT, dust, ACPs and activated gases [4].

Tritium release mainly consists of the following: leakage from the tokamak cooling water system (TCWS), vacuum vessel, detritiation system (DS) or water detritiation system (WDS); outgassing from components and waste in the hot cell facility; outgassing from waste and effluents stored in the radwaste facility. Activated dust originates from the following: vacuum vessel cleaning operations; refurbishment operations of vacuum vessel components; waste management operation performed in the hot cell facility. ACPs mainly originate from the TCWS. Initially present in the form of suspended metal particles and soluble ions. ACPs are carried in exhaust gases. Activated gases are the gases potentially activated by neutron flux. The gases mainly consist of the following: air outside the cryostat; inert gases injected into the divertor and vacuum vessel.

Under the normal operation, radioactive gaseous effluents are transferred into the ventilation and detritiation systems after originating and transferring into various systems. The treated effluents are released to the atmosphere through a common exhaust located on the roof of the tokamak complex.

2.2. Possible radioactive release under the worst hypothetical accident

To determine the general dose results, unit gram release source terms in the preliminary safety report

(RPrS) of ITER and dose conversion factor for inhalation (for dust and ACPs, particle size is 1μm) in ICRP-119 were referred [4][14] and shown in Fig.1. To ensure safety, a safety limit was defined for ITER to allow at most 1kg tritium and 1000kg dust in vacuum vessel. And both were mobilizable under severe accidental condition. On the basis of the near-universal recognition, ITER is the fusion reactor with two confinements (vacuum vessel and Tokamak building) above the fourth generation reactor.

In the vacuum vessel, explosion including flammable gas (hydrogen isotopes, ozone and CO), metallic and combustible dusts is possible to happen. The internal explosion may damage the confinement systems. Former studies have performed the public dose assessment under the beyond design basis accidents (BDBA) for ITER shown in the literature [4], and found the BDBA would damage to vacuum vessel and cryostat resulting in large holes. Because the second confinement (tokamak building) works, the radioactive gaseous effluents will be purified by the ventilation and detritiation systems. Therefore, the radiological impact is only about 4mSv after BDBA named wet by pass. However, it is an interesting issue whether the tokamak building can still work under the hypothetical accident condition.

Actually, external hazard (terrorist aircraft crash, earthquake, etc.) can also damage the tokamak building and its sub-systems inside. Former accident like Fukushima showed it was possible to damage the containment building (penetration piece) and lead large radioactivity to release into the atmosphere, at last developing into INES level 7 accidents.

According to the new understanding of Defense in Depth theory (DiD) after the Fukushima accident, there is a possibility that one hazard leading to multi-failure of the multi-barrier system, which will lead to the worst consequences (Just like the Swiss Cheese Model). Thus, we cannot completely eliminate the occurrence likelihood of both vacuum vessel and tokamak building failing to work when the internal hazard (resulting in vacuum vessel in large holes) and external hazard (resulting in penetration piece of tokamak building destroyed just like Fukushima accident) happened at the same time (Fig.2). It is sure the occurrence probability of the hypothetical accident is very low. We still need to discuss the public radiation impact if both the internal hazards and external hazards happened at the same time.

For the real release source terms, it is a complex and difficult work as there is not a real fusion reactor although many large experimental devices (e.g. JET, TFTR, JT60) have been under operation for many years. Thus, there is not a clear viewpoint on the release source terms for fusion reactor. Former works performed by

LLNL in USA summarized the maximum release fraction (mobility category) for fusion reactor based on analysis at MIT, combined with test data from INEL [15,16]. In the summary report [16], gaseous tritium (HTO) belonged to the Category I defined as elements gaseous or extremely volatile under thermochemical conditions of normal operation. And the release fraction is 100%, which is also the same as release fraction of noble gases from fission reactor into environment. Tungsten dust belonged to the Category IV defined as elements somewhat volatile under conditions that may be encountered in severe accidents. And the release fraction is 1%~10% [16]. Therefore, the most confidence interval of release source terms under the worst hypothetical accident is 100% of gaseous tritium (1000g HTO) and 1%~10% of dust (1000kg tungsten dust). As for the 100% of dust release, it is almost impossible. To comprehensively make the assessment, we considered two cases for comparison showed in Table 1 as the release source terms to perform the possible accidental consequences.

2.3. Dose assessment code

The study of public dose assessment plays a central role in site radiological consequence analysis. In this work, TAS3.0 was used to assess individual dose due to tritium (HT, HTO) release on the basis of puff model [17], and HotSpot3.0 was used to assess individual dose due to other radionuclides release on the basis of general plume model [18].

TAS3.0: the version3.0 of Tritium Analysis program for fusion System (TAS) was developed by FDS team in our earlier works as an analysis tool for use in assessing tritium environmental safety for fusion reactor, based on the first version of assessing tritium self-sufficiency and tritium fuel management for steady operation of fusion reactor, the second version for pulsed fusion reactor. In the tritium environmental safety module, the atmospheric dispersion, migration in soil, metabolism in biota, dose assessment processes are considered for normal operation and accidental events of fusion reactor. Verifications were performed with UFOTRI on the basis of ITER benchmark, HotSpot3.0 on the basis of Canada HT release experiment in 1987 [17]. Besides, dynamic tritium behavior in the environment was simulated with reasonable results after released from fusion reactor [19].

HotSpot3.0: HotSpot Health Physics Codes, or HotSpot program, was developed by Lawrence Livermore National Laboratory of the USA, provides a first-order approximation of the radiation effects associated with the atmospheric release of radioactive materials. The program was created to equip emergency response personnel and planners with a fast, field-portable set of software tools for evaluating incidents involving radioactive material.

2.4. Conservative environmental condition

To get the relative reasonable conservative dose results, the selection of release source terms, time of accident, meteorological conditions, release height, and receptor position should be reasonable pessimistic.

As for the receptor position, the maximum early dose position must be some place in the downwind distance away from the release point when the single wind direction was assumed during the exposure. For the nuclear facility, site boundary must be defined in its SAR (safety analysis report). For ITER, site boundary was defined as 1000m to eliminate the off-site emergency [4-6]. As ITER is the first fusion reactor, many safety issues of ITER will be referred for the fusion demonstration reactor (DEMO) and fusion power plant (FPP) safety target. Therefore, to get the reasonable conservative dose results, receptor position must be larger than 1000m referred to ITER site boundary.

For the release height, under the hypothetical accident (assumed both vacuum vessel and tokamak building destroyed), it is impossible to make sure the radioactivity were still released from stack to the atmosphere. Thus, it is reasonable to assume the release height as ground release (10m) [7].

To get the relative conservative duration of release, rain rate, atmospheric stability, wind speed and the receptor position, sensitivity analysis of the parameters above should be also performed. A benchmark of the parameters must be set before performing the sensitivity analysis. The preliminary parameters were set that duration of release is 10minutes, no rain rate, B atmospheric stability, 0.3m/s of wind speed and 1000m of site boundary under ^{187}W (1g dust) accidental release. Under the condition mentioned above, the sensitivity analysis was carried out using HotSpot3.0 and the results were shown in Fig.3. It is shown the relative conservation condition is instantaneous release source, F atmospheric stability, 0.3m/s of wind speed and 1000m of downwind distance. As for the rain condition, radioactive material in the air would be washed to soil under the rain condition. Thus, it is sure the inhalation dose at 1000m will below the condition without rain. For the external exposure, the external exposure dose might be larger than the condition without rain if the receptor position is near the release point. But the dose is also below the condition without rain at 1000m. On the other hand, in the evaluation of early dose, inhalation exposure dose is dominant. Therefore, the conservative weather condition is that it does not rain.

Comprehensively considering all of the relative reasonable conservative conditions (summarized in Table 2), the relative conservative public dose was performed. Firstly, unit gram release source term was defined to get early dose of different unit radioactivity release. Secondly, the possible dose was evaluated under the worst hypothetical accident mentioned above. At last, the accidental consequences related to public were also assessed.

3. Results and discussion

3.1. Public early dose of 1g radioactive accidental release

For tritium accidental release, the inhalation and skin absorption exposure pathways were considered to assess the early dose after the instantaneous release (a puff). For other radionuclides release, both inhalation and external exposure pathways were considered. For the time of exposure, external exposure only considered the early dose in the first 4 days after the accident, internal exposure (inhalation in the first 4 days) considered the integrated dose equivalent of the next 50 years. Based on the source terms in Fig.1 and basic input parameters in Table2, the public early dose (4 days) in 1000m away from the fusion reactor was evaluated due to unit gram tritium (T), dust, ACPs and activated gases release. The results were shown in Fig.4 and indicate that:

1) For 1g T accidental release, the early dose of 1g HTO release is about dozens to hundred times larger than which of 1g HT releases.
2) For 1g dust release, the dose of ^{187}W release contributes most to the total dust dose, followed by ^{185}W.
3) For 1g ACPs release, the dose of ^{60}Co release contributes most to the total ACPs dose, followed by ^{55}Fe.
4) For 1g activated gases release, the early dose of $^{14}CO_2$ release is 270mSv; the early dose of ^{41}Ar release is 1.9×10^{10}mSv.

To perform further dose evaluation, 1g T (HT), 1g T (HTO), 1g dust, 1g ACPs and 1g ^{14}C ($^{14}CO_2$) and 1g ^{41}Ar were defined as six release types. And the comparison was carried out. The results showed that the dose of 1g ^{41}Ar release is several billions times larger than other release source types. The dose of 1g $^{14}CO_2$ release is almost ten times larger than which of 1g HTO release. The dose of 1g HTO release is about dozens to hundred times larger than 1g dust release / 1g ACPs release / 1g HT release.

From the results, unit gram activated gases release will lead highest radiation dose, because of the shorter half-life of activated gases (especially for ^{41}Ar: 1.83hour). However, the total activity of activated gases (10^9Bq level: 10^7Bq/m^3 level, plasma volume is 840m^3) in the vacuum vessel is much lower than tritium (10^{17}Bq level) and dust (10^{17}Bq level) when considering the real mobilized inventory of activated gases, ACPs, tritium and dust. For ACPs, both the individual dose of unit gram and inventory amount (20kg: 10^{14}Bq level; Maximum mobilized: 1.3%) are much lower than tritium and dust [4]. Thus, under the hypothetical accidental case, the foremost concern should be tritium and dust in vacuum vessel.

3.2. Public early dose and INES level under the hypothetical accident case

Once the hypothetical accident mentioned above happened, it is possible the public early dose to achieve 419Sv for case 1 (almost impossible) and 23.99~59.9Sv for case 2 (most confidence interval), which is much larger than maximum public dose allowance (250mSv for fission reactor in China, 50mSv for ITER). Thus, delimitation of site boundary need be carefully discussed for fusion reactor, and related technology studies of restricting radionuclides release are required to ensure safety.

To better communicate these events with the public, a distinct phrase has been attributed to each level of INES. They are anomaly (level 1), incident (level 2), serious incident (level 3), accident with local consequences (level 4), accident with wider consequences (level 5), serious accident (level 6), and major accident (level 7). The highest four levels (level 4-7: accident) were defined its level by its radiological equivalence to a number of terabecquerels of ^{131}I. We calculated the radiological of ^{3}H and ^{187}W equivalence to ^{131}I using formula (1), and the ratios to ^{131}I are 0.0167 and 0.024 respectively on the basis of IAEA recommended method and data [13][20,21]. In the literature [13], the radiological of ^{3}H equivalence to ^{131}I is 0.02, which might be a rounding data of 0.0167. After evaluation, the definition of levels based on activity released and radiological equivalence to ^{131}I for released to the atmosphere were shown in Table 3. As well known, Three Mile Island (TMI) accident was defined as level 5. And Chernobyl and Fukushima accidents were defined as level 7. While, what about the fusion accident level on INES?

As can be seen from Table 3, INES level of 1kg tritium (3.56×10^{17}Bq) release, apart from 1000kg dust, will reach level 6. If considering 1000kg dust release (^{187}W: 1.04×10^{17}Bq) for case 1 and 10~100kg dust release for case 2, the total radiological of tritium and dust equivalence to ^{131}I is 8.4×10^{15}Bq for case 1 and 5.97×10^{15}Bq~6.19×10^{15}Bq for case 2. Thus, the results means the hypothetical fusion accident will reach level 6 according to INES.

As well known, thermal power of Chernobyl and Fukushima power plant is about 3000MW. Fusion power of ITER is only about 500MW. ITER-like DEMO power plant (such as European DEMO) is generally designed with the fusion power of 2000~3000MW, net electricity of several hundred MW. 1kg tritium and 1000kg dust were chosen as safety limit in vacuum vessel according to the public evacuation and the reasonable ITER operational scenario. For the DEMO fusion reactor with a comparable power with Chernobyl and Fukushima nuclear power plant, it is still under discussion that how to set the safety limit. Some hold that the inventory in DEMO could be lower due to the expected lower erosion rate of all tungsten plasma facing surface, more stable plasma operating scenario with fewer disruptions, higher tritium burnup fraction and current pumping system concepts (accumulated more tritium in cryopumps of ITER). But above viewpoint need be confirmed by performing related studies. Anyhow, currently safety analysis for European DEMO still assumed the same safety limit as ITER [22]. Therefore, for the future DEMO or FPP, it is likely the same level 6 accident on INES can only happen under the hypothetical condition.

$$R_{^{131}I} = \frac{\left(DCF_{inh.} \bullet I_{inh.} + v_d \bullet DCF_{ground}\right)_{radionuclides}}{\left(DCF_{inh.} \bullet I_{inh.} + v_d \bullet DCF_{ground}\right)_{^{131}I}} \qquad (1)$$

R_{I-131}:	Ratio to ^{131}I
$DCF_{inh.}$:	Dose conversion factor of inhalation in BSS, IAEA-safety series No. 115 (Sv/Bq) [20]
$I_{inh.}$:	Breathing rate ($3.3\times10^{-4}m^3/s$)
V_d:	Deposition velocities (0.01m/s for I, 0.0015m/s for other materials)
DCF_{ground}:	Dose factor for 50-year dose from ground deposition in IAEA-TECDOC-1162 ($Sv\times m^2/Bq$) [21]

3.3. Environmental restoration after the hypothetical accidents

After the hypothetical accident, the released radionuclides in the air will deposit in the surface of soil. Then the public will receive the radiation dose from the ground shine until the deposited radionuclides disappear (radioactive decay). The processes were shown in Fig.5. If migration in soil aside, radionuclides will stay in surface soil until its loss through the way of radioactive decay. That is the reason why we still cannot live in around the Chernobyl and Fukushima accidental site.

For the receptor position, assessment above referred to the site boundary (nonresidential) of 1000m, which is reasonable conservative, but may be not the position of maximum individual dose. After the hypothetical accident, the ITER like fusion reactor site might be abandoned like Chernobyl and Fukushima site. When assessing the environmental restoration time for resident, we need to perform the dose assessment on the basis of the maximum dose position around the fusion site because there is not concept of site boundary for an abandoned DEMO or FPP.

To get the maximum dose position (only ground shine exposure pathway) and conservative condition, sensitivity analysis of accident condition has been performed using HotSpot3.0. The results showed the maximum dose rate position is about 35m of downwind distance. And the conservative condition at the moment of accident is that the atmospheric stability is A, wind speed is 0.3m/s, release time and height is instantaneous ground release. According to the condition, the dose rates (dose per year) of ground external exposure (ground shine) were evaluated using the ground shine model of HotSpot 3.0 and radioactive decay equation (formula 2) after the hypothetical accident. Dose rates of various radionuclides and the total dose rates were shown in Fig.6. The results show that radioactive tungsten (^{181}W) contributes most to the external exposure because of its characteristic of higher special activity and dose conversion factor. As times goes by (radioactive decay factor: after 3~4 years), radioactive cobalt (^{60}Co) contributes most to the external exposure owing to its longer physical half-life (5.271 years).

As a result, according to the safety limit 1mSv/a, we should keep evacuation around the post-accident fusion reactor site at least 69 years for case 1 and 34~52 years for case 2 (none ingestion absorb, only external exposure), if do not take any measures to speed environmental restoration. And if taking the ingestion absorb of deposited radionuclide into consideration, the evacuation period of local residents will be even longer.

For the other receptor position around the accidental point, the contamination areas with the certain environmental restoration time after the hypothetical accident were shown in Fig. 7. The results showed the pollution area which need more than 24 year of environmental restoration is 0.26km^2 for case 1 and 0.0026km^2~0.026km^2 for case 2. And the pollution area (need more than 5 year of environmental restoration) is 3.2km^2 for case 1 and 0.033km^2~0.33km^2 for case 2.

$$\left(\text{Dose Rate}\right)_t = \left(\text{Dose Rate}\right)_1 \times \exp\left(-\ln 2 \times \frac{t-1}{T}\right) \qquad (2)$$

Dose Rate$_t$:	Dose rate (Sv per year) in the year of t after the accident
Dose Rate$_1$:	Dose rate (Sv per year) in the first year calculated by HotSpot3.0 after the accident
t:	Time after the accident (year)
T:	Half-life of radioactive materials (year)

4. Conclusions

The present work is to provide the comprehensive public radiation consequences due to tritium (HTO, HT), dust, ACPs and activated gases accidental release. From the analysis mentioned above, we can make the following conclusions.

1) Synthetically, taking dose factor and inventory of radioactivity in vacuum vessel into account, tritium and dust (W) are the most significant release type and should be the research concern under the hypothetical accident assumed in this work.
2) Under the hypothetical accident, the public early dose is much larger than maximum public dose limit after our preliminary simulation. Delimitation of site boundary need be carefully discussed for fusion reactor.
3) Fusion reactor can only happen level 6 accident on INES under the hypothetical condition. Level 7 accident like fission Chernobyl and Fukushima accidents will never happen in fusion reactor if safety limit of future DEMO or fusion power plant was not larger than ITER.
4) After the hypothetical accident, we need wait at least 69 years to live (none radioactive ingestion) for case 1 (1kg HTO and 1000kg dust) and 34~52 years for case 2 (1kg HTO and 10kg~100kg dust) around the fusion reactor if we don't take any measures to speed environmental restoration.

This work attempted to explain the conservative public radiation consequences on the point of public dose, INES level and environment restoration time when assuming the very low occurrence probability accident. The hypothetical accident probability is also important to be answered. Besides, more real accident sequence and thermal-hydraulic calculation of other types of accidents will be performed in the future.

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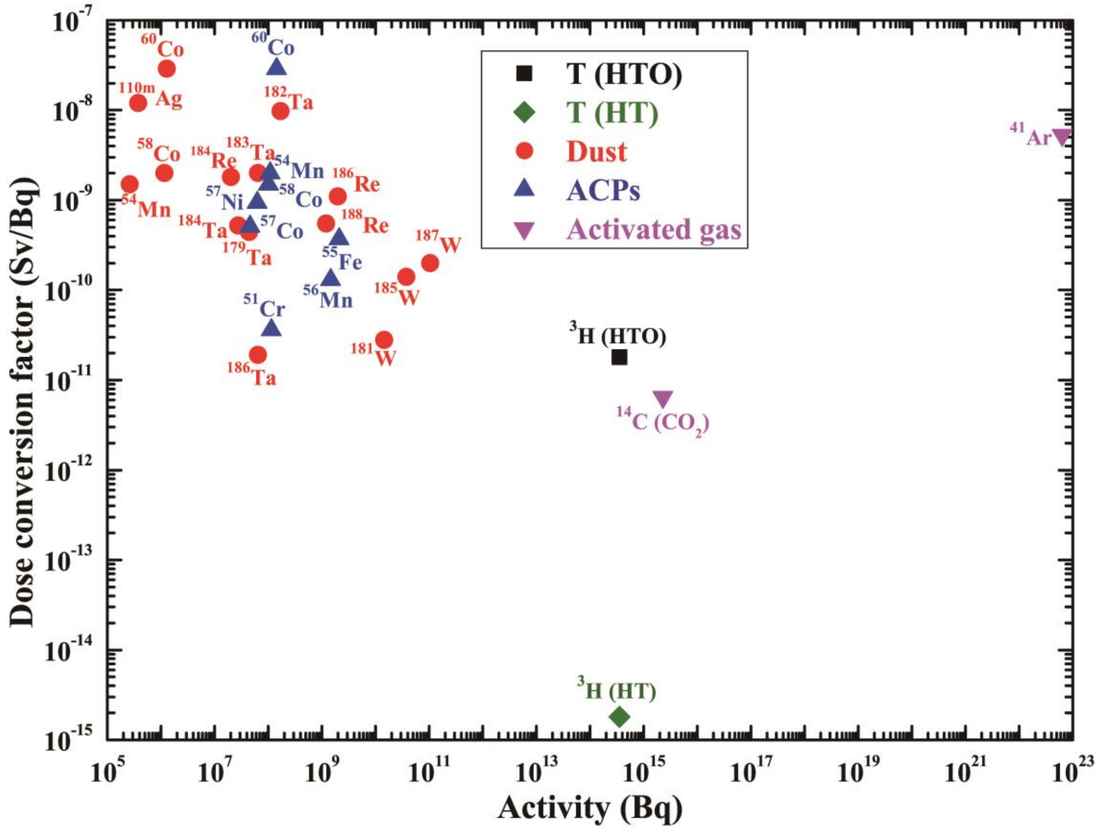

Fig. 1. Definition of unit gram radioactive gaseous effluents of fusion reactor.

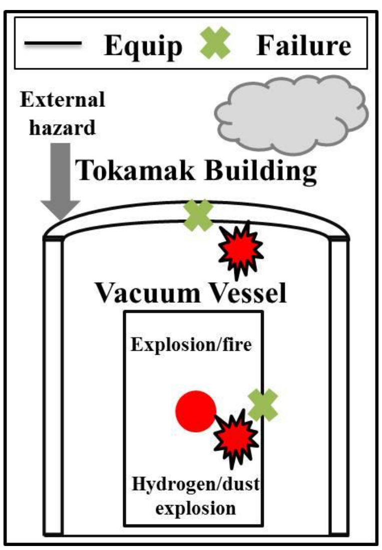

Fig. 2. Confinements and accident sequence of ITER-like fusion reactor under the hypothetical accidental case.

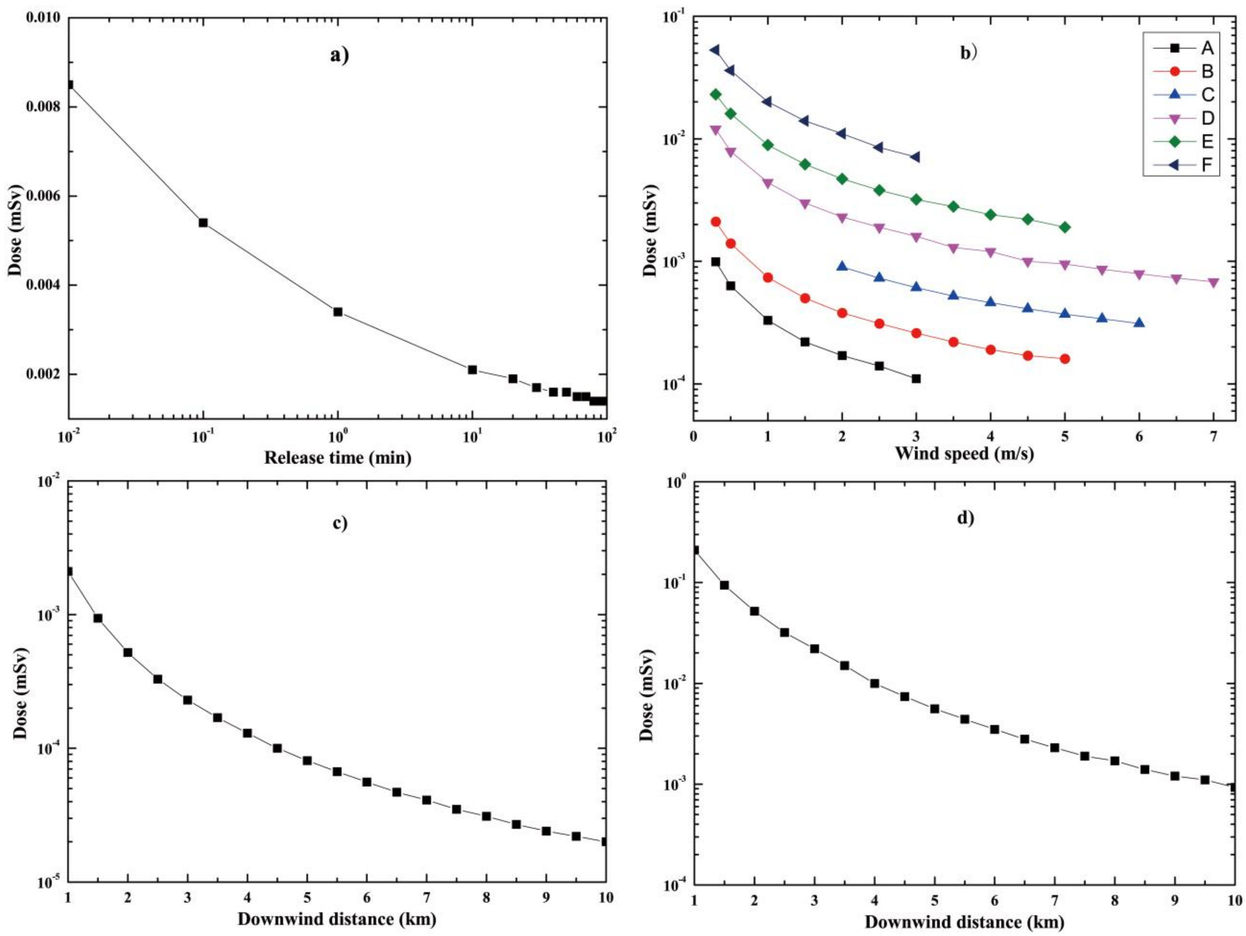

Fig. 3. Sensitivity analysis of accidental release time, wind speed in atmospheric stability and downwind distance. a) Individual dose in 1000m vs. accidental release time. b) Individual dose in 1000m vs. wind speed in different atmospheric stability. c) Individual dose under benchmark value vs. downwind distance. d) Individual dose under conservative value vs. downwind distance.

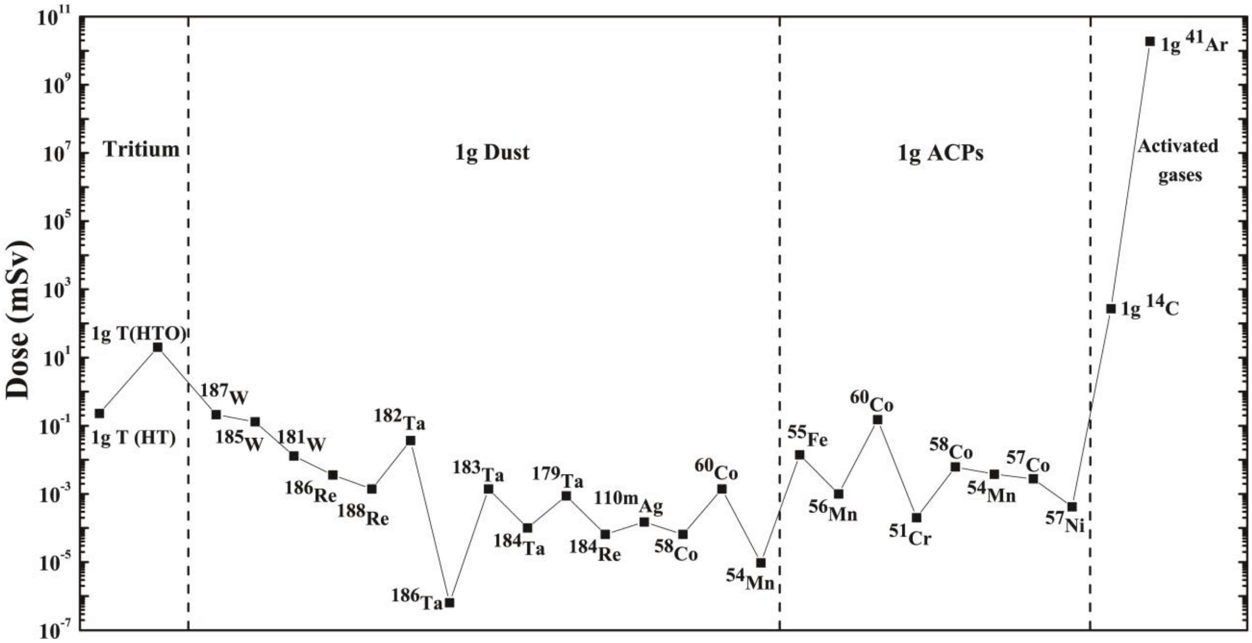

Fig. 4. Early dose due to unit gram source term accidental release.

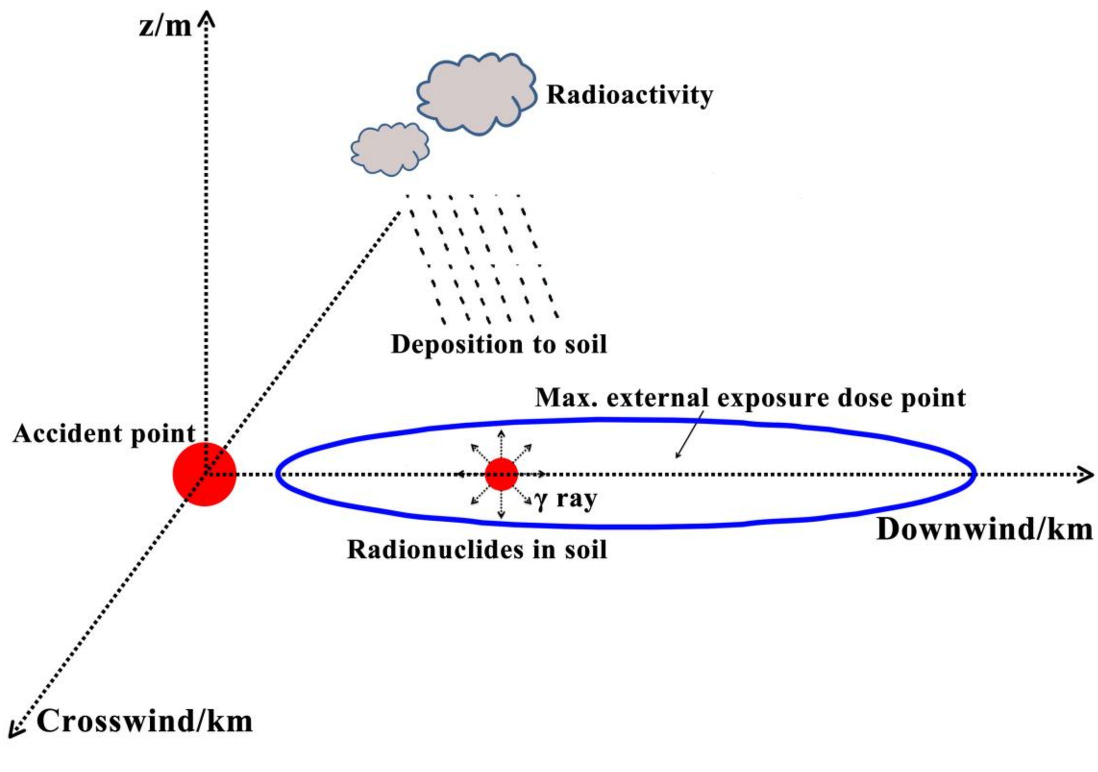

Fig. 5. Schematic diagram of long term external exposure due to radionuclides in soil.

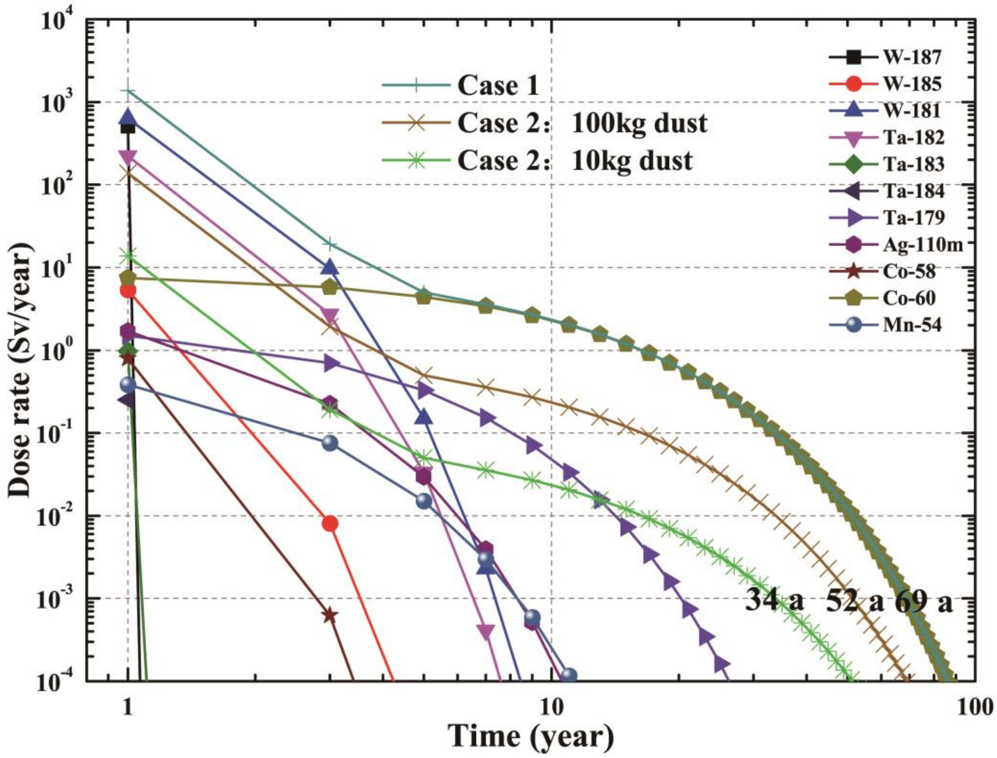

Fig. 6. Dose rate of radionuclides vs. time after the hypothetical fusion accidental ground release.

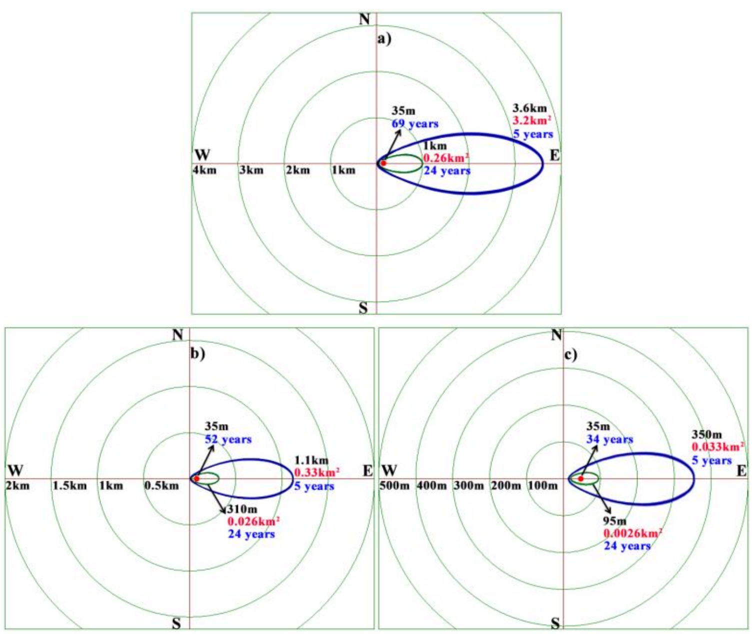

Fig. 7. Area of contamination and environmental restoration time after the hypothetical fusion accidental ground release. a) Case 1: 100% dust release. b) Case 2: 10% dust release. c) Case 2: 1% dust release.

Table 1. Possible release source terms of fusion reactor under the worst hypothetical accident.

	Tritium (HTO)	Tungsten dust
Case I: total source terms (almost impossible)	1kg	1000kg
Case II: most confidence interval	1kg	10kg~100kg

Table 2. Values of parameters implemented in TAS3.0 and HotSpot3.0 code.

Input parameters	Benchmark value	Conservative value
Release time	10 min	Instantaneous release
Wind speed (h=10 m)	0.3 m/s (calm)	0.3 m/s (calm)
Stability class	B	F
Downwind distance	1000m	1000m
Rain	No	No

Table 3. INES level definition and radiological of ^{3}H and ^{187}W equivalence to ^{131}I release under accidents.

INES	^{131}I (Bq)	^{3}H (Bq)	^{187}W (Bq)
7	$>5\times10^{16}$	$>3\times10^{18}$	$>2.1\times10^{18}$
6	$(5\sim50)\times10^{15}$	$(3\sim30)\times10^{17}$	$(2.1\sim21)\times10^{17}$
5	$(5\sim50)\times10^{14}$	$(3\sim30)\times10^{16}$	$(2.1\sim21)\times10^{16}$
4	$<5\times10^{14}$	$<0.3\times10^{16}$	$<2.1\times10^{16}$