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Integrated risk assessment method for spent fuel road transportation accident under complex environment

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ABSTRACT

Current risk assessment of Spent Nuclear Fuel (SNF) transportation has the problem of the incomplete risk factors consideration and the general particle diffusion model utilization. In this paper, the accident frequency calculation and the detailed simulation of the accident consequences are coupled by the integrated risk assessment method. The “man-machine-environment” three-dimensional comprehensive risk indicator system is established and quantified to characterize the frequency of the transportation accidents. Consideration of vegetation, building and turbulence effect, the standard k-ε model is updated to simulate radioactive consequence of leakage accidents under complex terrain. The developed method is applied to assess the risk of the leakage accident in the scene of the typical domestic SNF Road Transportation (SNFRT). The critical risk factors and their impacts on the dispersion of the radionuclide are obtained.

1. Introduction

Spent nuclear fuel transportation environment is composed of social condition, meteorological condition, and geographical condition, and there are invariably more complex socioeconomic conditions and much more uncertainty interference factors involved than that in the fixed locations. Once a transport accident occurs, the consequences are far-reaching and immeasurable, especially for complex terrain.

To date, there have been some studies on road and maritime transportation of the spent fuel. In these studies, when assessing the accident probability, the risk factors considered are incomplete, because most of them only consider the transport cask, while human errors and mechanical failures, as well as external environment interference are rarely considered. The Nuclear Regulatory Commission (NRC) [Ref.1] assessed the radiation consequences of different spent fuel casks to the crew and public by using the RADTRAN program. However, the accident probability used in risk assessment was obtained by averaging the traffic accident data covering the years 1991–2007 in US. Jeong et al. [Ref.2] have assessed and compared the risks of three accident scenarios of the SNF transportation by sea. Yet, the accident probability of the maritime and the road were also obtained by using the ship accident probability covering the years 1979–1993 and years 2000–2005 in Korea respectively. Dispersion model is a key technique for the consequence assessment, and many models have been used to simulate contaminant in atmosphere from 0 km to 1000 km, such as Gaussian model, Lagrangian model and Eulerian model [3,4]. Currently, when evaluating the radioactive consequences of the SNFRT, the general particle diffusion model was used to simulate the dispersion of the radionuclide. The RADTRAN program, which used by the NRC for radioactive consequences assessment, is a basic Gaussian dispersion model [1]. However, airflow field near the surface with a scale smaller than 10 km is changeable, where the dispersion of the radionuclide is mainly governed by turbulence. Gaussian model is hard to accurately simulate radionuclide dispersion under the complex environment.

In this work, a three-dimensional integrated risk assessment method coupled with Computational Fluid Dynamics (CFD) is

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developed, which can identify the key risk factors of the transportation system and calculate the radioactive consequence under multi-factor disturbances. Firstly, the occurrence frequency of the transportation accident is quantified by the proposed method. Secondly, consideration of vegetation, buildings and turbulence effect, the radioactive consequence of the leakage accident under complex terrain is assessed through the updated standard k-ε model.

2. Methodology

2.1. Estimation of the accident probability based on PSA method

In this paper, Probabilistic Safety Assessment (PSA) method is used to estimate the probability of the SNFRT accidents. The method mainly consists of three steps: The first step is the establishment of the three-dimensional comprehensive risk indicator system, which includes SNFRT system analysis and critical initiating events identification. The second step is the Event Tree (ET) modeling for transportation accident of the spent fuel under complex environment. The third step is the Fault Tree (FT) modeling for pivotal functional events and initiating events.

2.1.1. Initiating events identification

The risk factors of the SNFRT accident are obtained based on the detailed analysis of the SNFRT system. This system mainly consists of six elements: human, truck, spent fuel cask, transport road, surrounding environment, and management. When a SNFRT accident occurs on the highway, the accident will result in transport cask damage or cause radioactive materials leakage. Such accidents are caused by interaction of many factors related to human errors, mechanical vehicle failures and environmental conditions. In this study, based on our previous work about probabilistic safety assessment for spent fuel road transportation [Ref.5], the "man-machine-environment" three-dimensional comprehensive risk indicator system is presented, which is used to identify and classify contributing factors in SNFRT accident. Detailed lists of these indicators are shown in Table 1.

Initiating events are caused by the three-dimensional comprehensive risk factors. These factors interact and are interrelated, triggering different accident scenarios that varies in time and space. Initiating events combing and grouping should be based on these accident scenarios. Transport cask will lose efficacy when the mechanical load and thermal load generated exceed the cask stress threshold in an accident. According to the possible action modes of spent fuel road transportation accidents, the accident scenarios can be categorized by five accident stresses: collision, crush, puncture, fire, and immersion, of which collision and fire are the main scenarios leading to the failure of the spent fuel transport cask. Collision refers to the cask colliding with an object and is produced in about 80% of all truck accidents [1]. Crush refers to the situation where the transport cask is partially or extensively rested between the ground and an overturned truck or other heavy structure. Puncture refers to the collision between the cask and the object and the cask is pierced. Fire refers to the cask being exposed to the high temperature environment caused by burning and are expected to occur in 1.6% of all truck accidents [1]. Immersion refers to the cask being immersed in a liquid medium, for example, the accidents in which the truck leaves the road and enter an adjacent body of water during bridge crossing. In this paper, we mainly consider impact (collision, crush, and puncture) and fire in the spent fuel road transportation accidents to comb the initiating events while immersion is not considered. Fifteen initiating events are identified based on the detailed analysis of the established risk indicator system, literature review, historical data collection, field research and expert consultation and we divided them into four groups according to different accident scenarios. Detailed lists of these initiating events are shown as follows:

(1) Mechanical vehicle failures: {flat tire (FT), truck fires (TF), steering wheel failure (SWF), engine intermittent flameout during up and downhill (EIF) [Ref.6], colliding with other vehicles while driving or emergency pull up (CV)}.
(2) Bad road environments: {poor road alignment: steep slope, sharp turning and long downhill (RA), poor road lighting condition at night and lack of safety-warning signs (LSF), the road slippery coefficient is less than 0.5, caused by rain or snow (SR) [Ref.7]}.
(3) Bad natural environments: {the horizontal visibility distance of the truck driver is less than 200 m caused by heavy rain, snow, fog, haze, or hail (HVD) [Ref.8], the truck encountered strong winds (gale) with force greater than level Ⅳ (GL) [Ref.9], geological disasters: earthquake, landslide, debris flow, and collapse (GDS), the surface temperature of the cask is higher than 80 °C resulting from air temperature (HT), thunder and lightning strike the transport cask (TLS)}.
(4) Bad social environments: {a nearby hazard explosion left the cask lying on flames with temperatures above 350 °C (HE) [10], the truck driver is driving on the highway and noticed animals suddenly cross ahead (ASC)}.

2.1.2. Event tree and fault tree modeling

After the identification and classification of comprehensive risk factors under different scenarios, this paper further explorers the cause and consequences of accidents by analyzing the relationship between comprehensive risk factors and SNFRT accidents using the ET analysis (ETA) and the FT analysis (FTA). At the same time, the calculation of the occurrence frequency of the accident sequences are obtained based on the ET and FT analysis. In ET model, the calculation is done for the failure sequences as well as success sequences. The ET modeling starts from the initial event to infer the

Table 1
Three-dimensional comprehensive risk indicator system for SNFRT accidents.

Risk indicators	Details
Human	Fatigue driving, speeding, negligence, illegal operation, operation mistakes, poor mental state, insufficient knowledge and experience, other violations, poor management.
Machine	Brake failure, steering wheel failure, puncture, engine flameout, tire fire, fuel tank fire, other mechanical vehicle failures, monitoring equipment failure, container packaging failure.
Road Environment	Slippery road surface, poor lighting condition, poor pavement roughness, poor linear design (steep slope, sharp turning, long downhill), lack of safety-warning signs.
Natural Environment	Bad weather conditions: rain, snow, fog, haze, gale, high/low temperature, thunder and lightning. Geological disasters: earthquake, landslide, debris flow, collapse.
Social Environment	Malevolent attack, traffic accident nearby, nearby vehicles, pedestrian crossing the road, animals crossing the road, major hazard sources nearby.

possible consequences according to the time sequence of the accident development, thereby identifying potential weak links in system. A single or combination of risk factors can trigger an initiating event. An initiating event, if triggered, may disrupt the balance of the transport system, and then cause a transport accident, which may finally lead to damage or radioactive materials leakage of the spent fuel cask under mechanical or thermal loads. Functional events can block the development of the initiating event, thereby preventing the occurrence of an accident or reducing its consequences. The safety mitigation systems in the transportation system act as the functional events in the event tree model.

The failure probability of the functional events and the occurrence frequency of the initiating events are obtained through the FT analysis. Human factors play vital roles in the road transportation accidents according to accident statistics and scientific literature. The failure threshold of the transport cask is closely related to the magnitude of the impact speed [5]. In view of this, this paper proposes the Human-Machine Coupled Deceleration System (HMCDS) FT model by considering the truck brake system failures and the driver errors. The success criteria of the HMCDS functional event is that the braking system is effective and the driver successfully completes the braking action. The success criteria of the same functional system are different in the impact and fire scenarios. To avoid double counting, human factors are only considered in functional events. We selected six critical functional events in the SNFRT system, they are the Human-Machine Coupled Deceleration System (HMCDS), the artificial cooling system, the impact limiter, the neutron shielding layer, the gamma shielding layer, and the spent fuel assembly shell.

To reduce risk management costs, we divided the SNFRT accident consequences into six different levels by considering the different failure degree of the functional events. In our work, we only consider the failure form of the SNF cask from the outside to the inside under the influence of the initiating events. Six different levels of the SNFRT accident consequences are: OK (No accident, the transport cask is safe), RD (Recoverable Damage, the damage of the cask is recoverable and the radiation dose level on the surface does not increase), LD (Limiter Damage, the cask limiter damaged and the radiation dose level increased), ND (Neutron Damage, the cask neutron shielding layer damaged), GD (Gamma Damage, the cask gamma shielding layer damaged), and FD (Fuel assembly Damage, spent fuel rods are broken and radioactive materials are released).

2.2. Solution of the radionuclide concentration based on CFD

In this work, the standard k-ε model is updated to simulate radionuclide dispersion under spent nuclear fuel transportation accident. The radionuclide dispersion model composes of two parts, airflow simulation and radionuclide concentration simulation [18].

2.2.1. Airflow simulation

The airflow is maintained as incompressible under the atmospheric environment, and the vegetation was treated as porous media and the momentum equation was updated by adding momentum source loss [11], to simulate the pressure loss caused by vegetation. The mass conservation equation and the momentum conservation equation as follows:

The mass conservation equation:

$$\frac{\partial u_i}{\partial x_i}=0 \tag{1}$$

The momentum conservation equation:

$$\begin{cases} \rho\dfrac{\partial u_i}{\partial t}+\rho\dfrac{\partial(u_j u_i)}{\partial x_i}=-\dfrac{\partial P}{\partial x_j}+\dfrac{\partial}{\partial x_i}\left[(\mu+\mu_t)\left(\dfrac{\partial u_i}{\partial x_j}+\dfrac{\partial u_j}{\partial x_i}\right)\right]+\rho g+S_{u_i} \\ S_{u_i}=-\lambda\left(\dfrac{1}{2}\rho u_i|u_i|\right) \end{cases} \tag{2}$$

Where $u_i(\mathrm{m \cdot s^{-1}})$ is the velocity of the airflow, $t(\mathrm{s})$ is the time, $\rho(\mathrm{kg \cdot m^{-3}})$ is the atmosphere density,$P(\mathrm{Pa})$ is the pressure, $\mu,\mu_t(\mathrm{kg \cdot m^{-1} s^{-1}})$ are the dynamic viscosity and fluid turbulent viscosity, respectively, $\mathrm{g}(\mathrm{m \cdot s^{-2}})$ is the gravity acceleration,$\lambda(\mathrm{m^{-1}})$ is the pressure loss coefficient.

2.2.2. Radionuclide simulation

For the transportation environment, the leaked radionuclide is affected by some factors, such as vegetation effect, building walls effect, radionuclides decay and deposition. The concentration equation needs to be updated as follows:

$$\frac{\partial C}{\partial t}+\frac{\partial(u_i C)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\Gamma_C\frac{\partial C}{\partial x_i}\right)+S_C-\left(\lambda_d+v_{\tilde{d/w}}\right)C \tag{3}$$

Where $C(\mathrm{kBq \cdot m^{-3}})$ is the pollutant concentration on the point of (x, y, z) at each time step,$\Gamma_c(\mathrm{m^2 \cdot s^{-1}})$is the turbulent diffusion coefficient,S_C $(\mathrm{kBq \cdot m^{-3} \cdot s^{-1}})$ is the source term of the leaked radionuclide, ρ is the radioactive decay constant $(=0.693/T_{1/2}$, $T_{1/2}(\mathrm{d})$ is the radioactive half-life), $v_{\tilde{d/w}}$is deposition term.

2.3. Calculation of the dose rate

The human body is irradiated due to the radionuclide dispersion in the atmosphere, the estimation of the dose rate can be solved by the following equation:

$$D_w=2.78\times10^{-10}\times C_w\times F_w \tag{4}$$

Where $D_w(\mathrm{Sv \cdot s^{-1}})$ is the dose rate of radiation cloud, $C_w(\mathrm{Bq \cdot m^{-3}})$ is the concentration of the radionuclide in the atmosphere on the surface,$F_w(\mathrm{Sv \cdot m^3 \cdot s^{-1}/Bq})$ is the dose conversion factor.

2.4. Risk calculation

The calculation of the single leakage accident sequence and the total risks are expressed by the following equation:

$$R_i=f_i\times p_i\times d_i\times\rho_i\times\pi\times r_i^2 \tag{5}$$

$$R=\sum R_i \tag{6}$$

Where$f_i(\mathrm{h^{-1}})$is the average frequency of the initiating event,p_i is the average failure probability of the functional event,$d_i(\mathrm{Sv})$ is the individual dose received to the maximally exposed individual for 1 h at a distance of 15 m from the cask carrying spent fuel, which is calculated by the standard k-ε model.$\rho_i(\mathrm{person/km^2})$ is the population density per square kilometer.$r_i(\mathrm{km})$ is the radiation radius, where π is equal to 3.14.$\mathrm{R}_i(\mathrm{person \cdot Sv \cdot h^{-1}})$ is the radioactive risk of a single leakage accident sequence caused by one initiating event,$\mathrm{R}(\mathrm{person \cdot Sv \cdot h^{-1}})$ is the total radioactive risks, which are caused by the twelve initiating events.

3. Case study

3.1. Scenario description

To verify the feasibility and effectiveness of the risk assessment methodology, a typical domestic SNFRT case is selected for the study. A spent fuel transportation truck, storing PWR fuel assemblies, travels from Daya Bay Nuclear Power Station to Gansu 404 spent fuel reprocessing Plant. It is assumed that the truck will travel 4000 km from the start to the end with a speed of 40 km per hour continuously. It is also assumed that the radionuclide leaked from the spent fuel vessel during the road transportation due to impacts or fires, and the radionuclide dispersed to surrounding environment as the airborne type.

Wang et al. [Ref.12] indicated that trees have a significant effect on the pollutant dispersion in the canyon, especially for the trees higher than the buildings. In this work, the geometry model of the spent fuel transportation is shown in Fig. 1 [18], the calculation domain has a ground area of 64 H × 70 H with a height of 8H (H = 18 m), which includes buildings, trees, and road in the middle of the domain. The width of the road is 2H, the distance from buildings to road is 2/3H, the trees, which is 1/3H width and 3/2H height, is located between the buildings and the road and the distance from buildings to trees is 1/3H. Along the positive direction of X axis and perpendicular to the buildings, airflow with 2 $\mathrm{m \cdot s^{-1}}$entered the domain through the inlet and exited from the outlet. Wall-A is near the direction of inlet and Wall-B is near the direction of outlet.

Based on the SNFRT accident scenarios, Firstly, the "Man-machine-environment" three-dimensional comprehensive risk indicator system and the ET/FT model are established. In this paper, the ET/FT integrated model for SNFRT is established based on the PSA software system RiskA [Ref.13], which was developed by the FDS team for the reliability and probabilistic safety assessment of large complex systems under the framework of Virtual Nuclear Power Plant in Digital Society Environment "Virtual4DS" [14]. Secondly, the occurrence frequency of the leakage accident is obtained using the ETA. At the same time, leakage accident is qualitatively analyzed based on the structural importance degree coefficient and the Minimal Cut Sets (MCS) of the FTA. Thirdly, the dispersion and the concentration of the ^{131}I are obtained using the updated k-ε model. It is assumed that the air is maintained as isothermal state during the spent fuel transportation, ambient temperature is about 20 °C corresponding to 1.2 kg $\mathrm{m^{-3}}$ airflow density. A leakage of the ^{131}I from the spent fuel vessel during the transportation is caused by impacts or fires, and the leakage point situated at the middle of the domain, 1 h of continuous emission of the ^{131}I is affected by the factors, such as airflow, building walls and trees. The leakage rate of the ^{131}I caused by the accident shown as following is 3.3 $\mathrm{kBq \cdot m^{-3} \cdot s^{-1}}$ corresponding to 0.72 μg $\mathrm{m^{-3}\ s^{-1}}$ mass flow, and the radioactive half-life is about 8.02d. Finally,equations (4), (5), and (6) are used to calculate the radioactive risk of the leakage accident.

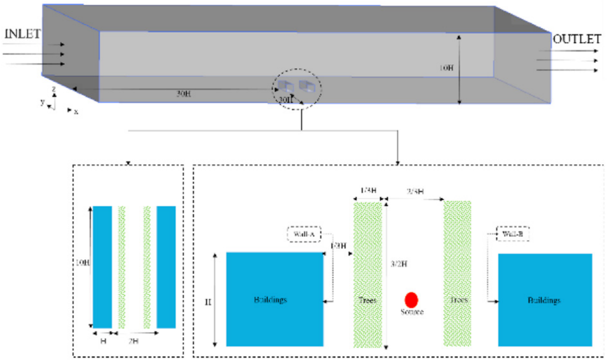
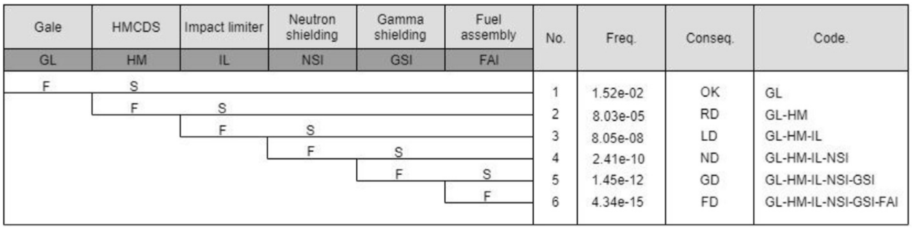


Fig. 1. Description of the spent fuel transportation scenario.

3.2. Results and discussion

Fifteen ETs are established based on the initiating events and the typical ET model is shown in Fig. 2. The initiating event GL in the ET model in Fig. 2 represent the truck encountered strong winds (gale) with force greater than level Ⅳ during the transportation process. Three vital FTs are established for the Human-Machine Coupled Deceleration System (HMCDS), Steering wheel failure (SWF) and Engine intermittent flameout during up and downhill (EIF). The FT model for HMCDS is presented in Fig. 3 and the description and failure probability of the basic events are given in Table 2. Eighty-four accident sequences are obtained. The occurrence frequency of the leakage accident is 4.7 × 10^{-12}/h. Through the leakage accident sequences analysis, a total of 1645 MCSs are obtained. That is, there are 1645 possible ways to cause SNFRT leakage accidents of the ^{131}I.

The ranking of the fifteen initiating events that lead to the leakage accident based on its occurrence frequency is: {Geological disasters (GDS) > Collision with other vehicles (CV)> Horizontal visibility distance less than 200 m (HVD) > Slippery coefficient of the road is less than 0.5 (SR) > Encountered strong winds with force greater than level Ⅳ (GL) > Poor road alignment (RA) > Engine intermittent flameout (EIF) > Lack of safety-warning signs (LSF) > Flat tire (FT) > Steering wheel failure (SWF) > High air temperature (HT) > Truck fires (TF) > the truck driver is driving on the highway and noticed animals suddenly cross ahead (ASC) > Thunder and lightning strike (TLS) > Nearby hazard explosion (HE)}. The results of the MCSs analysis suggested that the bad environmental condition is the most impact risk factor in causing SNFRT accidents, followed by the factors of the tractor driver, the vehicles (transport vehicle and vehicles around), and the bad road conditions.



Gale GL	HMCDS HM	Impact limiter IL	Neutron shielding NSI	Gamma shielding GSI	Fuel assembly FAI	No.	Freq.	Conseq.	Code.
F	S					1	1.52e-02	OK	GL
	F	S				2	8.03e-05	RD	GL-HM
		F	S			3	8.05e-08	LD	GL-HM-IL
			F	S		4	2.41e-10	ND	GL-HM-IL-NSI
				F	S	5	1.45e-12	GD	GL-HM-IL-NSI-GSI
					F	6	4.34e-15	FD	GL-HM-IL-NSI-GSI-FAI

Fig. 2. Typical ET model under impact caused by gale.

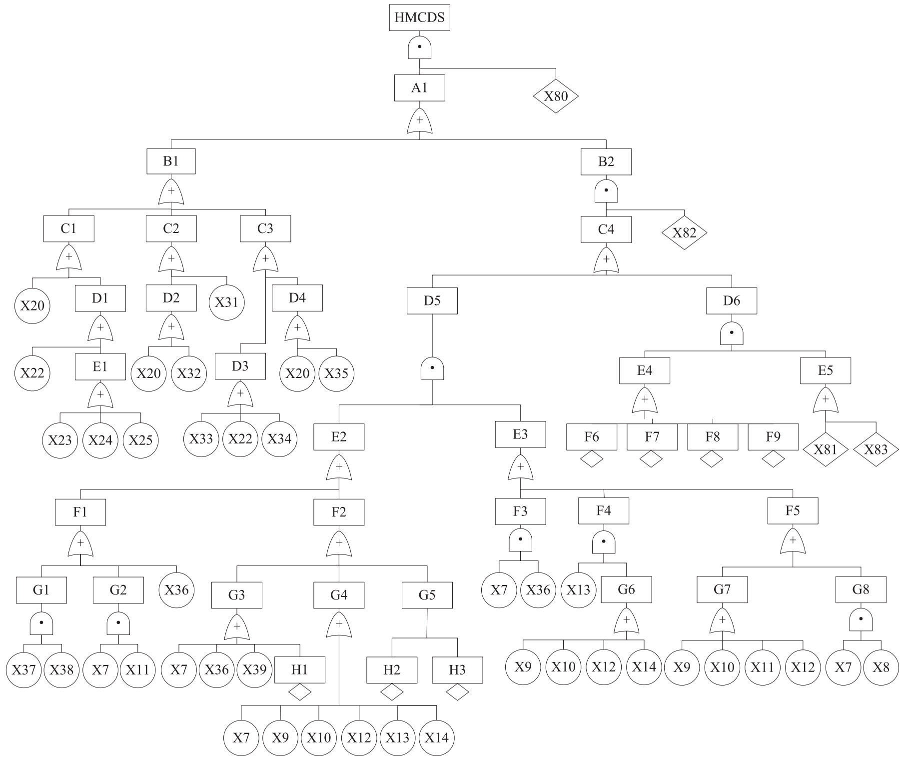


Fig. 3. Fault tree model for the HMCDS.

Fig. 4 shows the concentration of the ^{131}I at the z = 1.2 m leakage height where t = 3600th second, Fig. 3(a) shows the simulation of the ^{131}I under the no trees condition, and Fig. 3(b) shows the simulation of the ^{131}I under the trees condition. We found that the direction of the radionuclide dispersion is obviously opposite under the different conditions due to the wind speed and the turbulent vortex weakened effect. The cumulative dose for leak accident under the trees condition is 1.03×10^{-12} person·Sv, while under the no trees condition is 2.70×10^{-13} person·Sv. The average radioactive risks for radioactive material leak accident under the trees condition is 4.83×10^{-24} person·Sv·h^{-1}, while under the no trees condition is 1.27×10^{-24} person·Sv·h^{-1}. Obviously, the average radioactive risks under the trees is about 4 times than that under the no trees. The trend

Table 2
Description and failure probability of the basic events in HMCDS.

Basic events	Quick description	Probability	Data sources
X7	Insufficient knowledge and experience	8.00E-02	Literature [15]
X8	Low technical ability	3.00E-02	Literature [15]
X9	Fatigue driving	1.90E-01	Literature [15]
X10	Drugs and diseases	1.00E-03	Literature [15]
X11	Panic or nervous	2.50E-03	Literature [15]
X12	Drinking	2.15E-02	Literature [15]
X13	Speeding	1.60E-01	Literature [15]
X14	Poor reactivity	6.00E-03	Literature [15]
X20	Improper brake adjustment	5.00E-02	Literature [16]
X22	Rear brake rope failure	6.00E-02	Literature [16]
X23	Inner tube deformation	2.00E-02	Literature [16]
X24	Loose hook	1.00E-02	Literature [16]
X25	Front brake rope break	2.00E-02	Literature [16]
X31	One-sided rear brake cable damage	2.00E-02	Literature [16]
X32	Brake shoe damage	2.00E-02	Literature [16]
X33	Brake internal return spring failure	1.00E-02	Literature [16]
X34	Brake force return device spring failure	4.00E-02	Literature [16]
X35	Damper failure	1.00E-02	Literature [16]
X36	Negligence	1.10E-01	Literature [15]
X37	Inappropriate rules	2.00E-03	Literature [15]
X38	Psychologically handicapped	7.00E-03	Literature [15]
X39	Human-machine interface is not reasonable	4.00E-04	Literature [15]
X80	Failure of the emergency brake control device	2.00E-02	Assumption [17]
X81	Failure of hand lever	1.00E-02	Literature [17]
X82	Failure of the autonomous emergency braking system	2.00E-02	Assumption [17]
X83	Failure of mechanical linkage	2.00E-02	Literature [17]

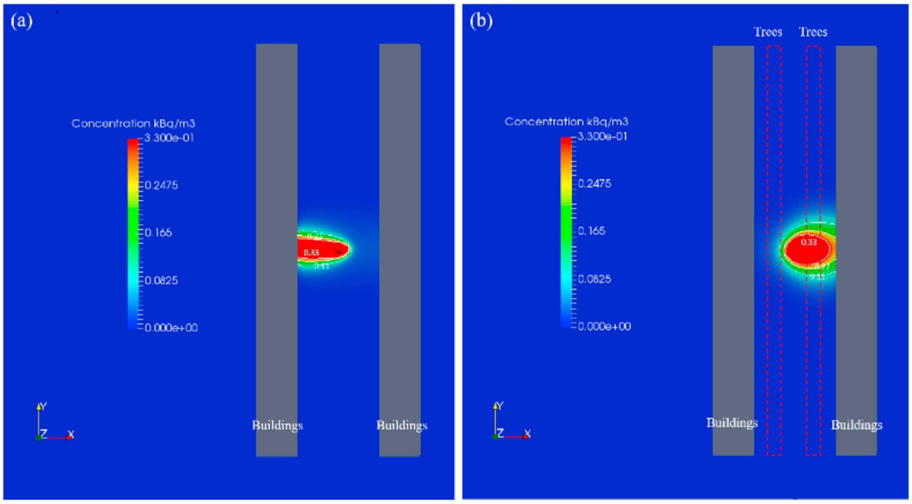


Fig. 4. Simulation of the ^{131}I at the z = 1.2 m leakage height where t = 3600th second (a) No trees; (b) Trees.

of the radionuclide dispersion and the cumulative dose can be predicted accurately through this integrated risk assessment method.

4. Conclusions

In this work, the “man-machine-environment” three-dimensional comprehensive risk assessment model is established by coupling the accident frequency calculation and the detailed simulation of the accident consequence. The standard k-ε model is updated to simulate radionuclide dispersion under the complex terrain. The transportation risk level is quantified by the proposed method and the underlying weakness of the transportation system is found through the accident sequence analysis. In addition, we found that the bad environment condition is the most impact risk factor in causing accidents, and the trees could weaken the turbulent eddy, which have a greater impact on the dispersion of radionuclide. The integrated method can not only effectively reveal the neglected high-risk units of the SNFRT system, but also can be used to provide technical support to the regional government to identify the blind spots and strengthen their risk management in the near future.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.09.030.

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