RADIOLOGICAL CONSEQUENCES ASSESSMENT OF A HYPOTHETICAL ACCIDENT DURING TRANSPORTATION OF SPENT NUCLEAR FUEL

by

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Scientific paper
https://doi.org/10.2298/NTRP180917003C

During the transportation of spent nuclear fuels, the potential release of the radioactive materials into the atmosphere in the case of an accident becomes a serious threat to public health and the environment. In China, a commercial reprocessing plant is planned to be commissioned around 2025 based on the China nuclear roadmap. After being cooled on site the spent nuclear fuels are transported to the reprocessing plant by train or truck. This requires the assessment of radiological consequences of such accidents during transportation, therefore dose calculations under hypothetical accident conditions have been presented in this paper. The total effective dose equivalent and ground deposition are calculated using the HotSpot health physics computer code with site-specific meteorological conditions. The results indicate that the total effective dose equivalent and ground deposition are both decreased with the increase of the downwind distance. The maximum of the total effective dose equivalent is about 1.4 10^{1} Sv, which is larger than the regulation limit for the public. The TEDE counter plot shows that the inner regions marked with dose contours of 1.0 10^{-3} Sv are higher than the regulation limits for the public, however this needs no intervention but any unnecessary trip to this area should be avoided.

Key words: radiological consequences assessment, atmospheric dispersion modelling, spent nuclear fuel, total effective dose equivalent, HotSpot

INTRODUCTION

The primary risk that nuclear power plants (NPP) present to public safety is due to the enormous amount of radioactive material released during accidents. Spent nuclear fuel (SNF) is defined as uranium-bearing fuel elements which have been used at commercial nuclear power plants and ought to be removed, owing to the insufficiency of these elements to generate ample energy to sustain a nuclear chain reaction. Even after removal of spent fuel assemblies from the reactor core, dissipation of heat and emission of radiations could not be ignored. The SNF is usually stored in spent fuel pools at NPP for cooling for several years. As the spent fuel pools capacity at reactors approaches its limit or SNF that will be reprocessed, the SNF are usually shipped to commercial reprocessing facilities or a nuclear waste repository. Whether SNF will be reprocessed or disposed, they will be transported to another location. A safety standard has been mentioned in guidelines issued by the International Atomic Energy Agency (IAEA) to ensure the safe transportation of radioactive material [1].

Spent nuclear fuel consists of radionuclides varying in their mass and activity, their characteristics depend on the type of reactor, burn up, fuel enrichment and cooling time and so forth. Therefore, to avoid the release of these radioactive materials, the transportation process of SNF should be strictly controlled.

However, in the case of a severe SNF transportation accident, spent fuel rods can be damaged resulting in exposure to radiation, causing severe health hazards to the public. Therefore, the IAEA has put forth safety standards and regulations to minimize the risk of accidents associated with transportation of these radioactive fuel elements. According to the NUREG-0170, the radioactive releases percentages of accidents associated with truck shipment is found to be 9 % while an associated percentage of 20 % exists for rail shipment [2]. The radiological dose calculation and consequences assessment for possible radionuclides release during a hypothetical accident is very important as far as human health and safety are concerned [3-6].

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The HotSpot Health Physics code, based on a Gaussian plume model (GPM), is used for radiation dose calculation and consequence assessment. The HotSpot code was established by the Lawrence Livermore National Laboratory (LLNL) to provide emergency response personnel with a fast, field-portable calculation tool for evaluating accidents involving radioactive materials which has been successfully applied in various radiological consequences evaluations [3-9].

In this study, the radiation dose calculations and radiological consequences of a hypothetical severe accident during SNF transportation have been performed by using the HotSpot code 3.03 [10]. The total effective dose equivalent (TEDE) and the ground deposition are calculated and discussed with varying climate conditions, to analyze radiological consequence assessment of SNF transportation.

MATERIALS AND METHODS

Site-specific conditions of SNF transportation

The Chinese reprocessing facilities will be placed in the Gansu Province, located in the northwest of China. According to the China nuclear energy roadmap, reprocessing facilities will be built and commissioned in about 2025. The considered region has an arid continental climate possessing significant annual variation in temperature in different seasons, and the rate of evaporation is larger than the precipitation. According to the meteorological conditions on the site, the predominant wind direction is north-north- west (NNW), which occurs for 50 % of the total time. The Pasquill stability class D is predominant with the annual average wind speed of 5 ms^{-1} for NNW.

Source term and accidental release scenario

In China, the closed nuclear fuel cycle policy is the only choice for the sustainable development of nuclear energy. The commercial reprocessing plant is planned to be put into operation around 2025 based on the China nuclear energy roadmap. Now, the SNF are usually cooled in a spent fuel pool on site of NPP. After that, they will be transported to a commercial reprocessing plant by train or truck. Owing to the associated risk, radioactive materials may be released into the environment if a severe SNF transportation accident happens. The accident source term can be obtained from the spent fuel inventory cooled three years and the release fraction of different radionuclides. The transportation cask by rail is assumed to carry 26 pressurized water reactor (PWR) assemblies, and for this case, it is supposed that one of the PWR assemblies has been damaged resulting in radioactivity release after the accident. The spent fuel inventory can be calculated by the burnup code ORIGEN-2 [11]. The main radionuclides are classified into five release groups, inert gas, caesium, ruthenium, particulates, and Chalk River Unidentified Deposits (CRUD). The release fractions applied to the calculated accident release activity as having values of 1, 0.33, 0.00002, 0.000027 and 0.0066 for CRUD, inert gas, particulates, ruthenium and caesium respectively [12-15]. The accident source term for SNF transportation is shown in tab. 1.

The program's stability class D is predominant justifying its use in this study. Nevertheless, other atmospheric stability classes are considered in this study. The standard value for mixing layer height (1300 m) and the default value of receptor height 1.7 m is used for the calculation, as the receptor height has a significant effect on TEDE. The accidental release

Table 1. Accident source term for SNF transportation

Radionuclide	Group	SNF cooling 3 years	Release fraction	Activity released [Bq]
Fe-55	CRUD	$3.51\ 10^{13}$	1	$3.51\ 10^{13}$
Co-60	CRUD	$2.05\ 10^{15}$	1	$2.05\ 10^{15}$
Kr-85	Inert gas	$1.38\ 10^{15}$	0.33	$4.55\ 10^{14}$
Sr-90	Particulates	$1.12\ 10^{16}$	0.00002	$2.25\ 10^{11}$
Y-90	Particulates	$1.12\ 10^{16}$	0.00002	$2.25\ 10^{11}$
Pu-238	Particulates	$1.05\ 10^{15}$	0.00002	$2.09\ 10^{10}$
Pu-239	Particulates	$2.36\ 10^{13}$	0.00002	$4.73\ 10^{8}$
Pu-240	Particulates	$5.24\ 10^{13}$	0.00002	$1.05\ 10^{9}$
Pu-241	Particulates	$1.27\ 10^{16}$	0.00002	$2.54\ 10^{11}$
Cm-242	Particulates	$8.34\ 10^{13}$	0.00002	$1.67\ 10^{9}$
Cm-244	Particulates	$8.11\ 10^{15}$	0.00002	$1.62\ 10^{11}$
Ru-106	Ruthenium	$2.49\ 10^{16}$	0.000027	$6.73\ 10^{11}$
Cs-134	Cesium	$2.59\ 10^{16}$	0.0066	$1.71\ 10^{14}$
Cs-137	Cesium	$2.20\ 10^{16}$	0.0066	$1.45\ 10^{14}$

height was assumed at 1.1 m, buoyancy and exit momentum effects were neglected. The radionuclide activity released into the atmosphere environment is immediately picked up by the wind and transported downwind according to the site meteorology. The annual average wind speed at 10 m is 5 ms^{-1} in the predominant direction of NNW, and the breathing rate is taken to be 3.33 10^{-4} m^3s^{-1} for an average human being under conditions of exercise [9]. Wind speed and rainfall rates are also considered in this study.

Radiation dose calculations

Owing to plume passage, TEDE was computed by the addition of both an effective dose equivalent (EDE) and the total committed effective dose equivalent (CEDE). The EDE was due to the external material including submersion, ground shine and resuspension, whereas CEDE was a result of internal material like inhalation. CEDE was performed by multiplying the integrated radionuclide concentration, χ, with an appropriate dose conversion factor (DCF), breathing rate (BR), and tissues weighting factors, W_T. A summation is provided of all the radionuclides

$$\mathrm{CEDE}(x, y, z) = BR\chi(x, y, z) \sum_{i=1}^{n} DCF_i W_{T_i}$$

where DCF and W_T are selected from the Hotspot library. The default release duration of radioactive material which is 10 minutes was applied in our calculation.

RESULTS AND DISCUSSION

Influence of different atmospheric stability classes

The TEDE and ground deposition distribution resulting from accidental release with different atmospheric stability are calculated. There are six different atmospheric stability categories used in HotSpot, varying from A (extremely unstable), B (moderately unstable), C (slightly unstable), D (neutral), E (slightly stable), and F (moderately stable). The average wind speed of 5 ms is chosen in this analysis, with the assumption of no rain. The curve of TEDE and ground deposition distribution with different downwind distance under different atmospheric stability are shown in figs. 1 and 2, respectively.

It has been shown in figs. 1 and 2 that the TEDE and ground deposition decreased with the increasing of the downwind distance and the TEDE of atmospheric stability A is smaller compared with others. The vertical dispersion of radioactive aerosols also increases with an increase in the instability of atmosphere, which reduces the concentrations deposited at a particular position. As the atmosphere becomes stabler, the radiation dose tends to increase gradually. The radiation dose reaches its highest value for the atmospheric stability which is E and F. It seems strange that the TEDE and ground deposition of E stability are greater than F stability at the end of the curve. The reason is that the worst-case stability at large downwind distances is not always associated with the greatest stability due to the plume depletion effects, as the plume concentration decreases at a faster rate with increasing stability class (A-F) and increasing deposition velocity. The E stability could result in a higher local concentration than F at a specific location due to LESS plume depletion associated with E stability [13].

The TEDE of stability class E is about 39 times the TEDE of class A at about 400 m downwind, with the increase of the downwind distance, which is about 82 times at 6 km. The more unstable the atmosphere, the more obvious the dilution of the radioactive aerosol, the more stable the atmosphere, the more serious the radiation harm caused. The maximum TEDE of D stability is about 1.4 10^1 Sv, which is larger than the

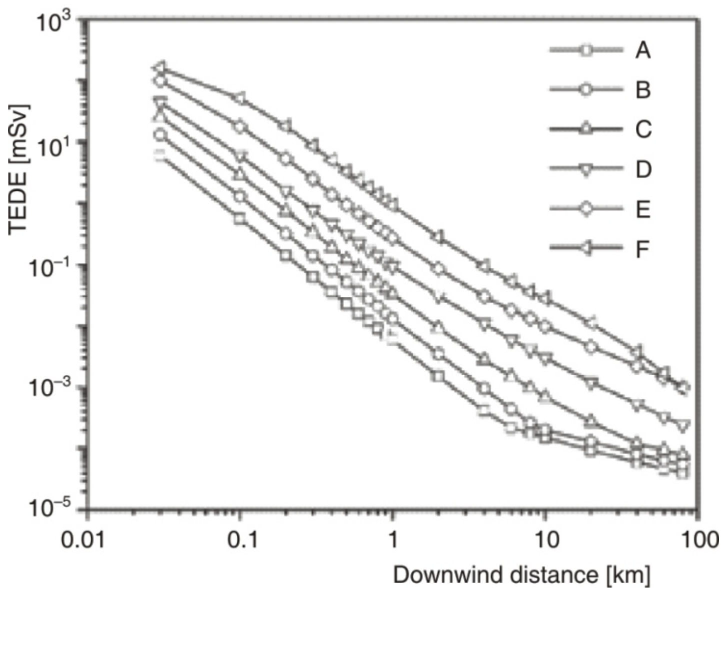

Figure 1. The TEDE as a function of downwind distance in different stability classes

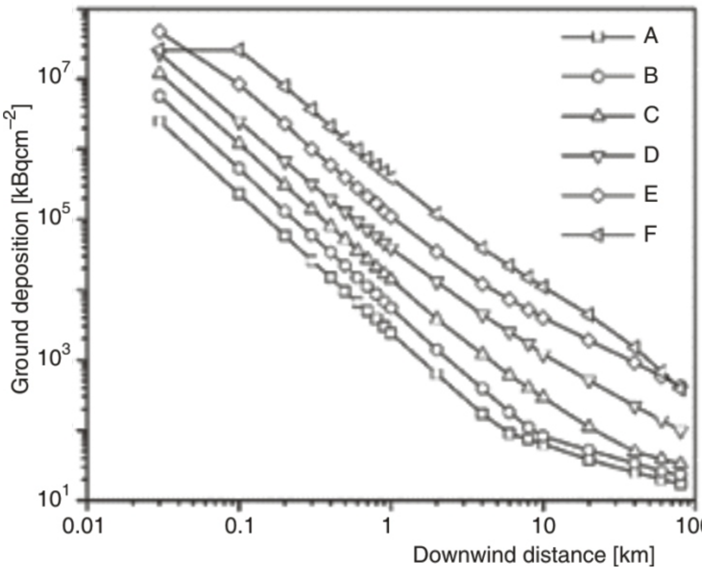

Figure 2. Ground deposition as a function of downwind distance in different stability classes

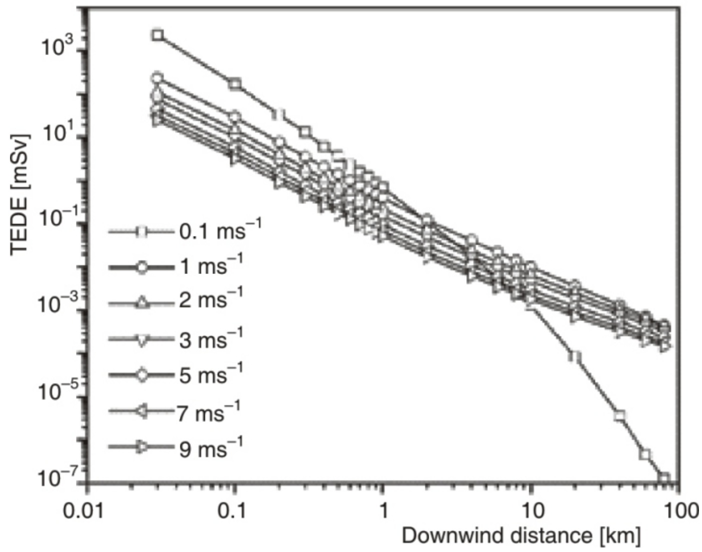

Figure 3. The TEDE as a function of downwind distance in at different wind speeds

maximum public dose limit. When the downwind distance is about 8 km, the TEDE is gradually below the annual regulatory limits of 1mSv for the public as set in the IAEA Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, GSR Part 3.

Influence of different wind speeds

The wind speeds at ground height of 10 meters are chosen for studying the effects of different wind speeds on TEDE and ground deposition. In this calculation, the atmospheric stability category is D (neutral), and the rainfall rate is 0 mmh^{-1}. The TEDE and ground deposition results under seven different wind speeds (0.1, 1, 2, 3, 5, 7, 9 ms^{-1}) are shown in figs. 3 and 4, respectively.

The TEDE and ground deposition both decreased with the increase of wind speed in normal weather conditions. It is very obvious that the TEDE and ground deposition of 0.1 ms^{-1} wind speed is largest except the distance larger than 2 km, and there is a sharp decrease for the curve of 0.1 ms^{-1}. The 10 m hight wind speeds of 0.1 ms^{-1} are very close to calm wind conditions, which is not conducive to the radionuclides diffusion and dilution. By comparison at about 200 m downwind, the TEDE and ground deposition of 1 ms^{-1} wind speed, are about three times the TEDE and ground deposition of 3 ms^{-1} wind speed, are nine times of 9 ms^{-1} wind speed. With the increase of the downwind distance, the proportion of the radiation dose caused by wind speed is basically unchanged except for the curve of 0.1 ms^{-1}. The larger wind speed is very convenient for reducing the harm of radionuclides, thereby based on conservative safety analysis, the small wind speed should be used for calculation of consequence assessment. The ground deposition at the wind speed of 9 ms^{-1} is smaller than at other speeds, because radionuclides are usually transported to further downwind distance by wind.

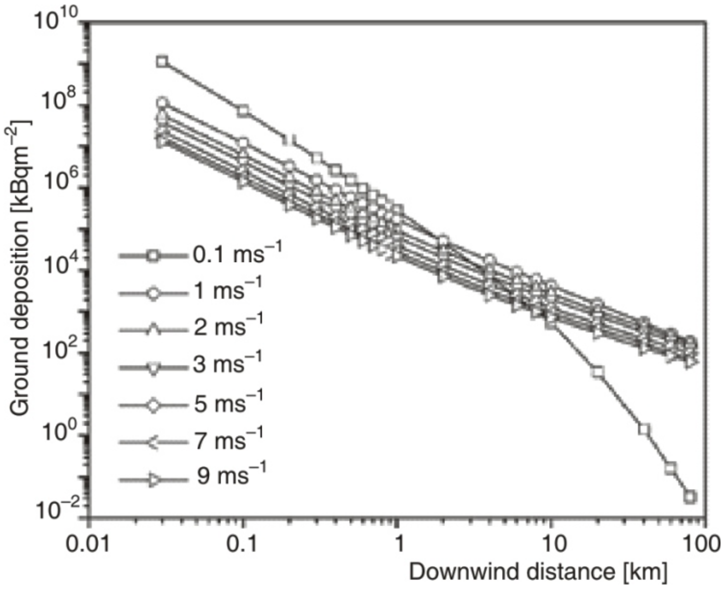

Figure 4. Ground deposition as a function of downwind distance at different wind speeds

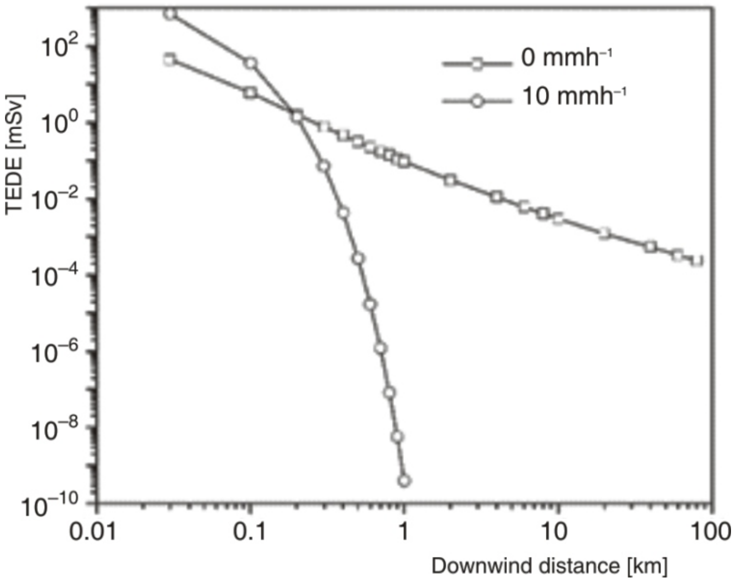

Figure 5. The TEDE as a function of downwind distance at different rainfall rates

Influence of different rainfall rates

Precipitation can remove radioactive material from a plume, so the effects of rainfall rates of 0 and 10 mmh^{-1} are analysed. The considered atmospheric stability and wind speed are class D and 5 ms^{-1}, respectively.

The impact of different rainfall rates on the TEDE and ground deposition of the SNF accident is shown in figs. 5 and 6, respectively. It can be seen that the rainfall rate has an obvious impact on the TEDE and ground deposition. The TEDE and ground deposition decreased with the increase of the rainfall rate, which was more obvious with the increase of downwind distance. Although the TEDE of zero rain is approximately equal to 10 mmh^{-1} rainfall rate at the downwind distance of 200 m, but the TEDE of zero rain is about 1150 times than 10 mmh^{-1} rainfall rate at the downwind distance of 500 m. By comparison, the ground deposition of no rain is about 3 times than 10 mmh^{-1} rainfall rate at the downwind distance of 300 m, but the ground deposition of no rain is about 3320 times greater than 10 mmh^{-1} rainfall rate at the downwind distance of 600 m.

In addition to this, figs. 7 and 8 show the TEDE contour plot under the plume specified for stability class D and wind speed of 5 ms^{-1} in dry and rainy weather conditions, whereas figs. 9 and 10 depict plume contour ground deposition distribution in dry and rainy weather conditions. It can be seen from fig. 7 that three regions with the area of 31 km^2, 81 km^2 and 741 km^2 have been marked with dose contours of 1.00 10^{-3}, 5.00 10^{-4}, and 1.00 10^{-4} Sv. However, as is shown in fig. 8, three regions with the area of 0.044 km^2, 0.050 km^2 and 0.066 km^2 has have been marked with dose contours of 1.00 10^{-3}, 5.00 10^{-4}, and 1.00 10^{-4} Sv. Meanwhile, it can be seen from fig. 9 that three regions with the area of 1.6 km^2, 36 km^2 and 857 km^2 have been marked with deposition con-

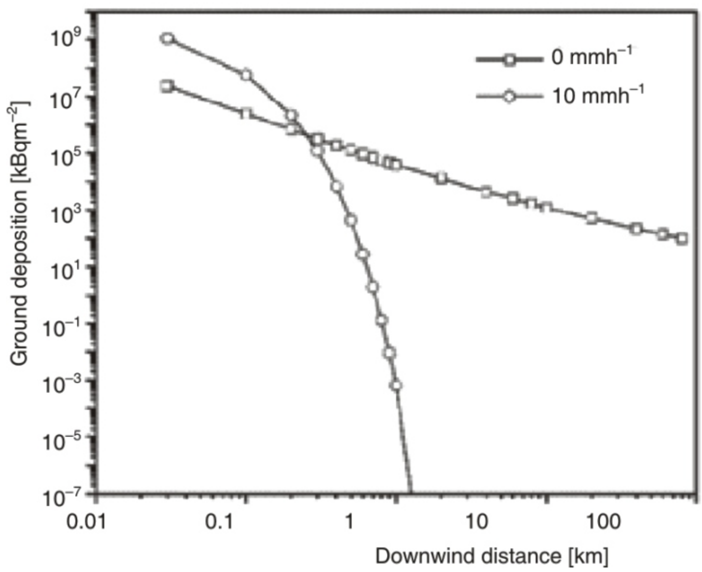

Figure 6. Ground deposition as a function of downwind distance in at different rainfall rates

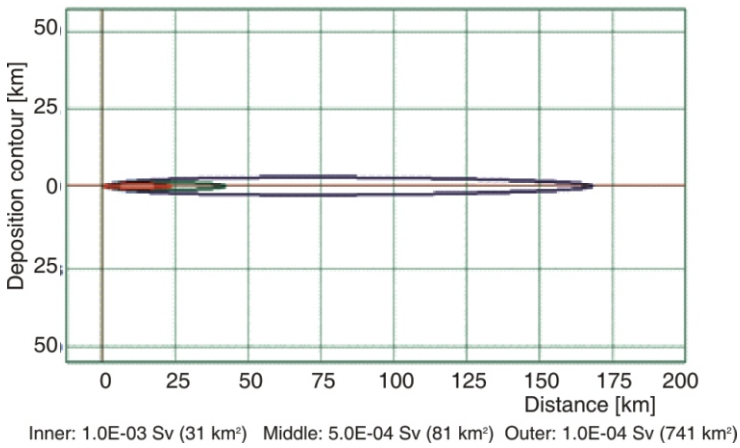

Figure 7. The TEDE counter plot for D class in dry weather

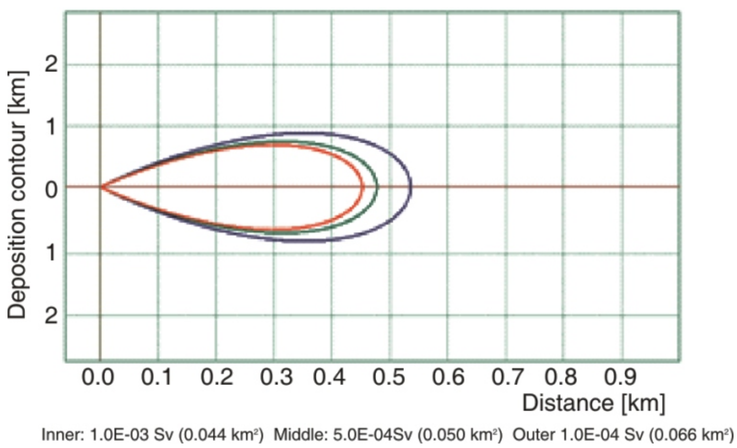

Figure 8. The TEDE counter plot for D class in rainy weather

tours of 3700, 370, and 37 kBqm^{-2}. Moreover, in fig. 10, three regions with the area of 1.6, 36, and 847 km^2 has have been marked with deposition contours of 3700, 370, and 37 kBqm^{-2}. The inner area in fig. 8 will do higher dose risk for personnel and population, which refer to the TEDE is higher than the maximum public dose limits recommended by the International commission on radiological protection (ICRP) which is 1 mSv per year.

This modelling result is probably attributable to the air concentration of radioactive material decreased because of precipitation. Rainfall caused the consumption of radioactive aerosol in the air, thus increasing the deposition of radioactive material. Internal radiation dose decreases with the increase of the rainfall rate, and the dose from external exposure increases with the increase of the rainfall rate. Wet and dry depositions, which caused internal radiation dose decrease,

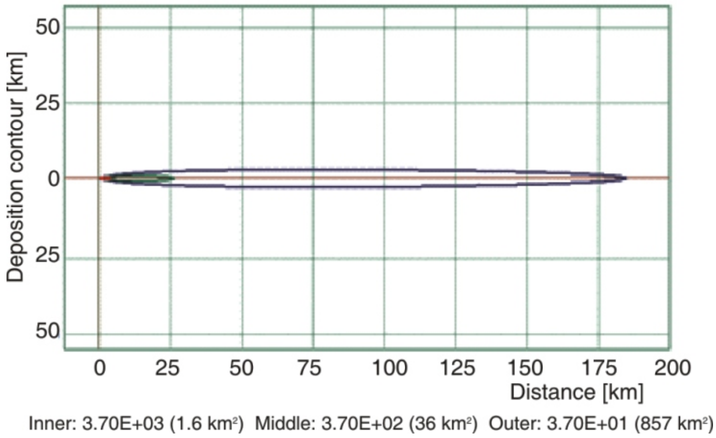

Figure 9. Plume contour ground deposition distribution for D class in dry weather

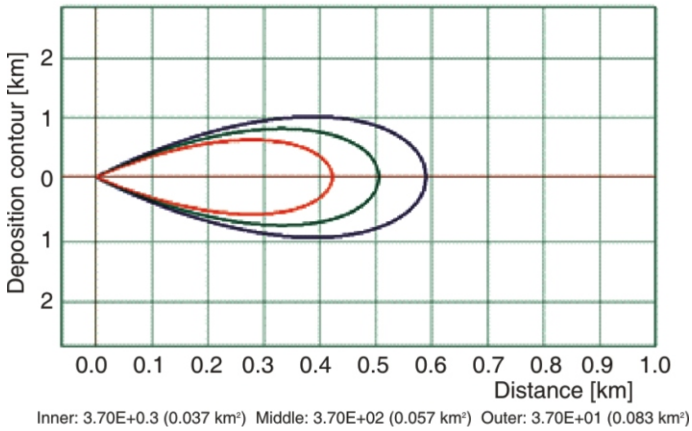

Figure 10. Plume contour ground deposition distribution for D class in rainy weather

are the main factors for reducing the TEDE. From the short-term safety evaluation of nuclear emergency, the high rainfall rate resulted in a lower radiation dose.

CONCLUSIONS

In this article, the radiation dose calculations and radiological consequences of a hypothetical SNF transportation accident have been performed by using HotSpot code 3.03. After the SNF accident, TEDE and the ground deposition are calculated at different meteorological conditions. The results indicate that the TEDE and ground deposition are both decreased with the increase of the downwind distance. By comparison with TEDE of different class stability, it can be concluded that the more unstable the atmosphere, the more obvious the dilution of the radioactive aerosol, the more stable the atmosphere, the more serious the radiation harm caused. With the increase of the downwind distance, the proportion of the radiation dose caused by wind speed is unchanged. The results show that the higher wind speed is very convenient for reducing the harm of radionuclides. As different rainy weather was considered, rainfall caused the consumption of radioactive aerosol in the air, and the deposition of radioactive material increased. The maximum of TEDE is about 1.4 10^1 Sv, which is larger than the regulation limit for the public. Therefore, the near-field staff should leave the accident site as soon as possible and go to the upwind direction to avoid contamination. In addition, appropriate measures should be taken to remove radioactive particles attached to the body. When the downwind distance is about 8 km, the TEDE is gradually below the annual regulatory limits of 1mSv for the public as set in the IAEA Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, GSR Part 3. The TEDE counter plots show that the inner regions marked with dose contours of 1 10^{-3} Sv are higher than the maximum public dose limit set by the ICRP. Taking into account the possible changes in wind direction, the public within 8 km of the accident point should be evacuated urgently. The public in other regions should avoid unnecessary travel to this area.

AUTHORS' CONTRIBUTIONS

The idea and results for the presented research were initiated and performed by B. Cao. The data processing and graphic presentation were carried out by

B. Cao and W. Cui. All the authors participated in the discussionn of the results presented in the final version of the paper.

ACKNOWLEDGMENT

This research was financially supported by the National Natural Science Foundation of China (11605059), the Fundamental Research Funds for the Central Universities (2018MS042) and the China Scholarship Council (CSC).

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Received on September 17, 2018
Accepted on February 18, 2019

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ПРОЦЕНА РАДИОЛОШКИХ ПОСЛЕДИЦА ХИПОТЕТИЧКОГ АКЦИДЕНТА ТОКОМ ТРАНСПОРТА ИСЛУЖЕНОГ НУКЛЕАРНОГ ГОРИВА

Потенцијално ослобађање радиоактивних материјала у атмосферу приликом транспорта ислуженог нуклеарног горива представља озбиљну опасност по опште здравље становништва и животну средину. Према нуклеарном програму Кине планиран је почетак рада комерцијалне фабрике за репроцесирање око 2025. године. Након хлађења ислуженог нуклеарног горива на локацији предвиђеној за ту активност, транспорт горива до фабрике за репроцесирање обављаће се железницом или камионима. Из овога настаје потреба за проценом радиолошких последица услед могућих акцидената током транспорта и у овом раду је приказан прорачун доза хипотетичког акцидента у оваквим околностима. Применом програмског пакета HotSpot израчунати су тотални ефективни дозни еквивалент и таложење радионуклида у земљишту користећи адекватне метеоролошке услове за дату локацију. Резултати указују да тотални ефективни дозни еквивалент и таложење у земљишту опадају са повећањем растојања. Максимална вредност тоталног ефективног дозног еквивалента износи око $1.4\ 10^{1}$ Sv, што је изнад прописане граничне вредности за становништво. График вредности TEDE приказује унутрашње области оивичене дозним контурама од $1.0\ 10^{-3}$ Sv у којима је доза већа од прописане вредности за становништво, без захтева за интервенцијом, при чему треба избегавати непотребне одласке у те зоне.

Кључне речи: процена радиолошких последица, моделовање атмосферког расипања, истрошено нуклеарно гориво, TEDE, HotSpot