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USE OF THE "HOTSPOT" CODE FOR SAFETY AND SECURITY ANALYSIS IN NUCLEAR POWER PLANTS: A CASE STUDY

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Abstract

Accidents in spent nuclear fuel reprocessing plants are a critical issue for the safety of people, of operators and the environment, as well as for the security of the plants. The purpose of this work is to demonstrate the possibility to use a free license code to simulate radiological diffusion after an accident in these particular plants, in order to obtain a model which allows identifying escape routes for the people potentially involved in the fallout. The authors performed a benchmark analysis of the data collected by the IAEA during the radiological accident of Tomsk. These data were further used to simulate general worst case scenarios. Numerical values of Total Effective Dose Equivalent (TEDE) generated in each "worst case scenario" where compared to the ICRP (International Commission on Radiological Protection) dose limits for acute exposition to radiation, in order to identify information on evacuation, sheltering and iodine prophylaxis in case of radionuclides release in conditions comparable to those analyzed. The authors achieved a good match between the numerical and field-results, giving a solid background to the worst case scenario simulations and allowing proposing a methodology for safety and security analysis with free license codes.

Key words: accident, nuclear, simulation

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1. Introduction

Due to the constant increase in the use of radioactive elements and nuclear energy, it became essential to acquire tools as decision support system (DSS) in case of radiological-nuclear events in order to get a reduction of the risks for the population and the environment

Nowadays, radioactivity is essential in many fields (medicine, industry, and energy production – Bellecci et al., 2009a, 2009b, 2010a, 2010b, 2011a, 2011b, 2011c, 2011d; Benedetti et al., 2011, 2013; Gaudio et al., 2010, 2011, 2013, 2015; Lupelli et al., 2015; Pinna et al., 2010). According to the International Energy Agency report on *Key World Energy Statistics* that contains timely, clearly-presented data on the supply, transformation and consumption of all major energy sources, the nuclear energy is becoming an attractive option for most developing countries due to its low-cost and other economical factors (IEA, 2012).

In different scenarios, reducing risk for radiological and nuclear events (either accidental or man-made) through technological improvements should be a priority (Cenciarelli et al., 2013; Fodor and Bányai, 2014; Gallo et al., 2013; Malizia et al., 2011, 2012, 2015), but it is clear that those risks shall never be completely eliminated. In this perspective, it is necessary to implement proper countermeasures in order to minimize the aforesaid risks.

A number of model and software tools have been developed over the years, which may be of use

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to organize RN first response based on predictive information on the radiological plume's direction (Ciparisse et al., 2015, 2016; Poggi et al., 2015), and on the airborne and ground concentration of radionuclides that are direct consequences of the radioactive fallout. While some of them (i.e. HPAC, NBC CREST, NBC Analysis) focus on the analysis of different kinds of threats – including the dispersion of chemical and biological agents – other software programs are specifically designed for RN events, such as RASCAL (USNRC, 2007) and HotSpot (Cacciotti et al., 2014; Gelfusa et al., 2015; NARAC, 2005).

Software applications for dispersion models are used to track the plumes evolution and estimate radionuclide hazards by inhalation, cloud-shine, ground-shine. The software used to predict physical parameters related to RN dispersal events enhances the information available and predicts dangerous scenarios. Nevertheless, measurements and comparisons with real data are necessary to validate and update predictions about the plume (Mikkelsen et al., 1984; Waller et al., 2009). Furthermore, radiological and nuclear accidents that occurred in the past are a unique and valuable source of information, which can be used in order to deal with similar events.

2. The Tomsk accident

2.1. Reprocessing plant and causes of accident

The Siberian Chemical Combine (SCC) is placed in the Tomsk region of Russia and it is composed by five nuclear reactors, a chemical separation plant (IAEA, 1998) (used as a processing facility for uranium, plutonium and uranium enrichment plants) and storage facilities for radioactive waste (Gauthier-Lafaye et al., 2008).

The radiological accident in the reprocessing plant at Tomsk has been widely described in the International Atomic Energy Agency's publication (IAEA, 1998). Also, the reprocessing procedure is well described by Malizia et al. (2014).

2.2. Radionuclides release due to the accident from the SCE (Siberian Chemical Enterprises) site

The accident located at the third level of the International Nuclear Event Scale (INES) caused damage to both the reprocessing line and the building, and resulted in the release of about 30 TBq of beta and gamma emitting radionuclides and about 6 GBq of ^{239}Pu isotope (IAEA, 1998). The radioactive material is mainly released in the environment through the large holes existing in the sidewalls and roof of the building which contains the damaged vessel.

Also some radioactive material was released through the 150 m high vent tube, but the amount of radionuclides that passed through the vent tube couldn't be precisely assessed due to the high velocity at which the gas escaped.

The release occurred with a steady southwesterly wind (blowing with a velocity between 8 and 13 m/s) causing the spread of radioactive material into the environment. The perimeter fence was 8 km long of the SCE, with additional 20 km stretching in northeast direction. Under these conditions, parts of the SCE site and a considerable area of the surrounding countryside to the north of the complex were contaminated with radionuclides (Fig. 1). The collection of soil samples on site and in the proximity of the site has been done around 4-5 weeks after the event. The total gamma and beta activity detected was aroud 4.3 TBq. The predictable activity (TBq) released in the course of the accident is shown in Table 1 of the published work by Malizia et al. (2014).

2.3. Releases information

There are two different sources of accident releases, as follows (Malizia et al., 2014):
1. the breaks in walls at a height of 15-30 m, which represented about 50-60% of the activity released;
2. the roof at a height of 100-150 m.

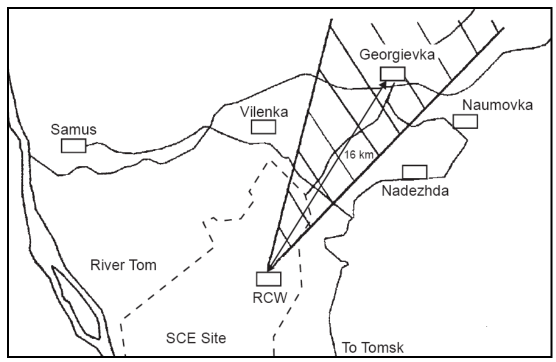


Fig. 1. Map showing the location of the SCE site and its boundary (broken line) with an impression of the direction and relative size of the contaminated area (IAEA, 1998)

Additionally, the measurement performed for assessing the contamination at ground level displayed an individuality entailing the occurence of two maxima in the deposited activity across the contaminated area, situated at right angles to the direction of the release, at distances up to 12 km from the Radio Chemical Works (RCW) (Malizia et al., 2014). This situation could be explained by supposing that the release from the roof and the walls of the RCW is redirected according to the wind directions, which was appraised as being different at diverse heights (190 degrees at ground level, and 210 degrees at 100-200 m height) (IAEA, 1998). The weather conditions are well described by Malizia et al. (2014).

3. The HotSpot code

HotSpot is a free license code that provides a fast method to evaluate the radiation effects associated with the atmospheric release of radioactive materials. It is based on a Gaussian model that estimates the short-range (less than 10 km), and short-term (less than a few hours) predictions for downwind radiological impact following the release of radioactive material.

The estimations produced by HotSpot are conservative and the Gaussian model implemented determines the time-integrated atmospheric concentration (C) of a gas or an aerosol at any point in space, according to an Equation presented by Homann (2011): direction are representative of observing plume characteristics over a time period of 10 min: this time is the "sampling time". Since the release may be of a greater or smaller duration, this parameter can be modified by introducing a correction factor for dispersion, σ'_y (Gifford, 1982; Hanna et al. 1982) (Eq. 1):

$$\sigma'_y = \sigma_y\, (t/10)^2 \qquad (1)$$

The essential values required by the model are:

- *the activity of the source term* involved in the scenario;
- *the meteorological data*: the wind velocity and direction and the solar insolation factor.

These data are required to determine the proper Pasquill's stability class (DeMarrais, 1978; Pasquill, 1961). The output generated allows visualizing both the ground contamination expressed in kBq·m^{-2}, and the total effective dose equivalent (TEDE) (USNRC, 2013a) expressed in Sievert (Sv) – which is defined in USNRC (2013b) (for external exposures) and the committed effective dose equivalent (USNRC, 2013c) (for internal exposures). The model was developed for both general releases of radionuclides and nuclear events, therfore, HotSpot allows the user to simulate the release of any radionuclide included in the ICRP 30 (ICRP, 1979) and in the ICRP 60+ (ICRP, 1991).

4. Benchmark for ground contamination due to ^{106}Ru

The input values of benchmark are well described by Malizia et al. (2014). The Deposition Velocity, which is a relevant parameter was estimated for the deposition of the beta-gamma emitters and was found to be of about 0.20 ms^{-1} (Shershakov et al., 1995). This was the value chosen for the benchmark. Options and values for the simulations were shown togheter with the spatial coordinates for down wind in Tables 3-5, included in the previously paper of Malizia et al. (2014). The outputs created by HotSpot with the sixteen combinations of values and options (Tables 3, 4, 6 from Malizia et al., 2014) were analyzed in order to understand which combination was the most appropriate to describe the pattern and the amount of ground contamination with ^{106}Ru.

As shown by Malizia et al. (2014), a wind speed of 5 ms^{-1} associated with Pasquill stability class "D" and a sample time of 1 min give a good match with the experimental data. These values have been plotted in Fig. 2 (a, b) as estimated ground contaminations for the two wind directions (190° and 210°) as a function of the downwind distance.

The HotSpot software also allows the user to visualize both the TEDE contour plots and Ground Deposition Contour Plots, which show the downwind and crosswind contours for dose levels and for the extent of the deposition respectively, and the TEDE Graph and Ground Deposition graph that display the relative values as a function of plume centerline downwind distance. The Ground Deposition contour plots for the two scenarios by Malizia et al. (2014) are shown in Fig. 2 (a, b). As expected from a Gaussian model, while the wind speed had a minor influence on the extent of ground contamination, the stability class and sampling time were the most influencing parameters.

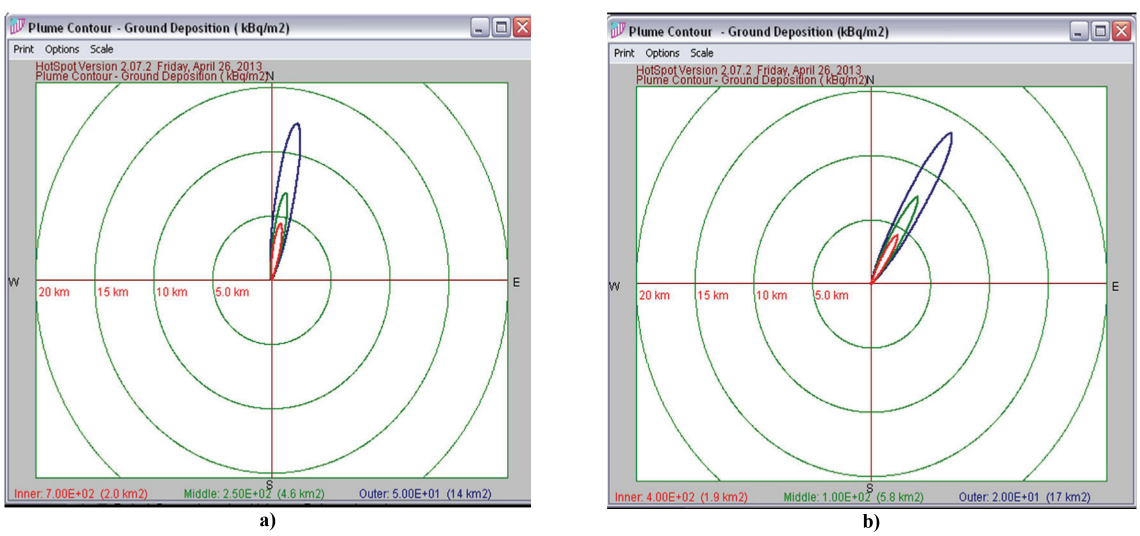


Fig. 2. Ground Deposition contour plot for the scenario described by Malizia et al. (2014): a) for wind direction 190°: the contour values for the plume are 7.0 E+02 kBq/m^2 (inner), 2.5 E+02 kBq/m^2 (middle) and 5.0 E+01 kBq/m^2 (outer); b) for wind direction 210°: the contour values for the plume are 4.0E+2 kBq/m^2 (inner), 1.0E+02 kBq/m^2 (middle), and 2.0E+01 kBq/m^2 (outer)

Stability class "C" that is a less conservative condition than stability class "D" entailed, for each distance from the release point, lower values for ground contamination compared to the experimental data. The effect of the sampling time was relevant as well, since the highest value for ground contamination with a 10-minute sample time was 440 $kBqm^{-2}$ at a downwind distance of 4.5 km for the release of 65% of the total activity. This is in good agreement with the model, since the downwind concentrations from a source decrease when sampling time increases.

The General explosion model resulted in a better match for the release of 65% of the total activity, which is assumed as originating from the cracks in the side walls, and also for the release of the 35% of the activity, which is assumed as originating from the 150 m stack. This may also lead to the reason that the second release may be better described by the "General Explosion".

It is also worth highlighting that applying a wind speed of 10 $m \cdot s^{-1}$ instead of 5 $m \cdot s^{-1}$ results in wider ground contamination. For this reason, we also considered a 10 $m \cdot s^{-1}$ when simulating the different worst case scenarios.

5. Worst case scenario

We simulated one more severe accidental scenario in order to evaluate the capabilities of software as a tool to help in managing radiological and nuclear emergencies. The authors hypothesized one different scenario (starting from the benchmark) represented by the HotSpot's "General Explosion" model and assumed that the total amount of Uranium and Plutonium estimated to be in the vessel (0.1 TBq and 1 TBq respectively) was involved in the simulated accidents. Then, we assumed that the releases occurred with the same wind direction, so as to evaluate a more severe scenario than the real accident, since if the fallout occurs in the same direction it will result in an additive effect. It should also be pointed out that, for the purposes of this work, the wind direction was arbitrary chosen as the average of the two wind directions reported for the accident in Tomsk.

The TEDE values resulting from the output of the simulations were used to evaluate the radial distance for the organization of evacuation,
sheltering and iodine prophylaxis according to the ICRP Publication 63 guide (ICRP, 1992; NARAC, 2005) for early response to a radiological or nuclear event:

- sheltering: 5 – 50 mSv (external dose);
- evacuation: 50 – 500 mSv (external dose);
- iodine prophylaxis: 50 – 500 (equivalent dose to thyroid).

These values were also used as dose contour values for the TEDE Contour Plots for the worst case scenario outputs.

5.1. "General Explosion" model: inputs

The total activity for Uranium and Plutonium in the vessel was estimated to be 0.1 TBq and 1 TBq respectively (IAEA, 1998, 2008). For the simulations involving these two radionuclides, the scheme of the benchmark for the release of ^{106}Ru was reproduced, excepting for the wind direction which, in this case study is assumed to be the same.

HotSpot allows the user to create a custom "radionuclides mixture" but, for the purposes of this work, the authors have chosen to evaluate each release separately, in order to have a better understanding of the contribution to the TEDE given by each radionuclide, and then merge the results from the individual simulations. The radionuclide mixture for 0.1 TBq of Uranium plus 1 TBq of Plutonium was also created to obtain the resulting TEDE plume for this scenario. The MAR for all these scenarios was considered as 100% of the total activity, since a single wind direction was chosen for all the releases. The values and options selected for the simulations (Explosion ^{238}U-100% and Explosion ^{239}Pu-100%) are reported in Table 1.

5.2. "General Explosion" model: output

The outputs generated by HotSpot for the release of the total amount of Uranium and Plutonium (0.1 TBq and 1.0 TBq respectively) were added together, and the resulting TEDE values were used to evaluate the distance for evacuation, sheltering and iodine prophylaxis. Tables 2 and 3 show the TEDE values as a function of the distance from the release point and the minimum distance for which the implementation of the above-mentioned countermeasures is required. Distances for iodine prophylaxis are not shown for the present and following simulations, since the threshold dose value to the thyroid have never been reached for all the "worst case scenario" simulations, due to the fact that the accident didn't involve a nuclear fission reactor.

Fig. 3 (a and b) shows the TEDE Contour Plot for the simulations conducted for the Uranium and Plutonium radionuclide mixture, both for 5 and 10 ms^{-1} wind speed; the values for all the downwind distances are the same as those deriving from the sum of the two releases.

Another important evidence is that, choosing a more conservative option, i.e. 5.0 ms^{-1}, results in a more "dense" TEDE in the proximity of the release. As a matter of fact, even though the minimum downwind distance where the value of 50 mSv is exceeded is the same for both simulations, the TEDE value for this point is higher for the most conservative option than in case of a 10 $m \cdot s^{-1}$ wind speed. On the other hand, choosing a less conservative option (a 10 ms^{-1} wind speed) results in wider contamination meaning, for this case study, the need to shelter wider part of the workers and population involved in the accident.

As expected, the main contribution to Total TEDE comes from the release of Plutonium assumed to be involved in the accident, due to its high specific activity.

Table 1. Options and values for Simulation ^{238}U-100% and Simulation ^{239}Pu-100% (Malizia et al., 2014)

	Simulation ^{238}U- 100%	***Simulation ^{239}Pu-100%***
Model	*General Explosion*	*General Explosion*
Source Term		
Radionuclide	U-238 D 4.468E9y	Pu-239 W 24065y
Material-at-Risk	0.1TBq	1 TBq
Deposition Velocity	20 cms^{-1}	20 cms^{-1}
Meteorology		
10-meter-wind-speed	5 ms^{-1} / 10 $m{\cdot}s^{-1}$	5 ms^{-1} / 10 $m{\cdot}S^{-1}$
Wind Direction	200°	200°
Stability Class	D	D
Setup		
Sample time	1 min	1 min
Non-breathable Deposition Velocity	20 cms^{-1}	20 cms^{-1}

6. Conclusions

Risk management for a radiological or nuclear event is essential since risk cannot be completely eliminated. Sound risk evaluation also allows implementing the right countermeasures to reduce the risk factors for the population. Atmospheric dispersion model software plays an essential role in these kind of events, because it is an essential DSS (Decision System Support) for operators in order to mitigate the magnitude effects of a radiological diffusion. It is worth pointing out that, due to lack of information on the release and to the limitations of the code, several approximations were made to create the benchmark scenarios; nevertheless the benchmark analysis conducted between HotSpot and the experimental data regarding the ground contamination with ^{106}Ru, resulting from the accident in the reprocessing of spent nuclear fuel facility at the SCE site in Tomsk showed the possibility to replicate the groud deposition scenario (with comparagble magnitudes) in different initial conditions (heights, wind speed and so on) demonstrating that the General Explosion model of the HotSpot code is a good optio to evluate the ground deposition of ^{106}Ru, for this particular scenario. It is reasonable to think that, with more detailed information regarding a release, the resulting benchmark would lead to a more accurate evaluation of the proper scenario and boundary conditions for the study of "worst case scenarios".

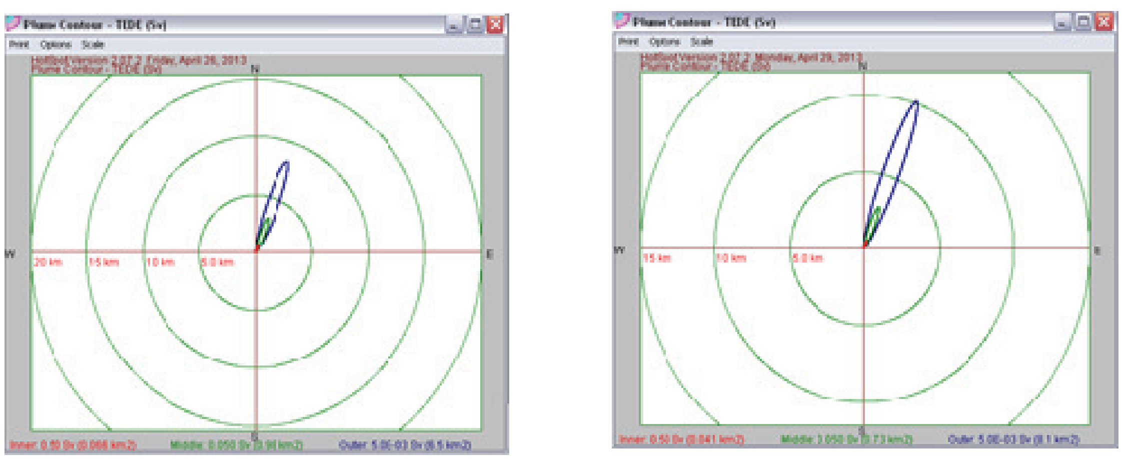
The results from the "worst case scenario" simulations conducted in this work showed that, in conditions similar to those identified in the benchmark, the main contribution to the TEDE is given, as expected, by the General Explosion model. On the other hand, the dispersion of the 35% of the total activity released during the hypothetical accident through a 150-m stack would result in smaller contribution to the TEDE. Basing on these observations, the General Explosion model provided by the HotSpot code may be used when data of a possible dispersion from stacks are not immediately available.

Table 2. TEDE values for each simulation and the Total TEDE for each scenario as a function of the downwind distance, for a wind speed of 5 ms^{-1} (the "X" in the columns indicates the necessity to implement the relevant countermeasure with respect to the downwind distance)

	Wind-speed: 5 $m{\cdot}s^{-1}$				
Down wind distance (km)	***^{238}U mSv***	***^{239}Pu mSv***	***Total TEDE mSv***	***Evacuation (500-50 mSv)***	***Sheltering (50-5 mSv)***
0.03	1.30E+01	2.20E+04	22013	**X**	**X**
0.1	4.50E+00	7.80E+03	7804.5	**X**	**X**
0.2	1.70E+00	3.00E+03	3001.7	**X**	**X**
0.3	9.80E-01	1.70E+03	1700.98	**X**	**X**
0.4	6.30E-01	1.10E+03	1100.63	**X**	**X**
0.5	4.80E-01	8.40E+02	840.48	**X**	**X**
0.6	4.00E-01	6.90E+02	690.4	**X**	**X**
0.7	3.30E-01	5.90E+02	590.33	**X**	**X**
0.8	2.90E-01	5.10E+02	510.29	**X**	**X**
0.9	2.50E-01	4.40E+02	440.25	**X**	**X**
1	2.20E-01	3.90E+02	390.22	**X**	**X**
2	6.90E-02	1.20E+02	**120.069**	**X**	**X**
4	1.70E-02	2.90E+01	29.017		**X**
6	6.20E-03	1.10E+01	11.0062		**X**
8	3.10E-03	5.50E+00	**5.5031**		**X**
10	1.80E-03	3.20E+00	3.2018		
20	1.80E-04	3.10E-01	0.31018		
40	1.10E-05	1.90E-02	0.019011		
60	1.50E-06	2.60E-03	0.002602		
80	3.70E-07	6.50E-04	0.00065		

Table 3. TEDE values for each simulation and the Total TEDE for each scenario as a function of the downwind distance for a wind speed of 10 ms^{-1} (the "X" in the columns indicates the necessity to implement the relevant countermeasure with respect to the downwind distance)

	Wind-speed : 10 m·s^{-1}				
Downwind distance (km)	***^{238}U mSv***	***^{239}Pu mSv***	***Total TEDE mSv***	***Evacuation (500-50 mSv)***	***Sheltering (50-5 mSv)***
0.03	7.00E+00	1.20E+04	12007	**X**	x
0.1	3.00E+00	5.30E+03	5303	**X**	x
0.2	1.30E+00	2.30E+03	2301.3	**X**	x
0.3	7.80E-01	1.40E+03	1400.78	**X**	x
0.4	4.90E-01	8.70E+02	870.49	**X**	x
0.5	3.50E-01	6.10E+02	610.35	**X**	x
0.6	2.70E-01	4.70E+02	470.27	**X**	x
0.7	2.10E-01	3.70E+02	370.21	**X**	x
0.8	1.80E-01	3.10E+02	310.18	**X**	x
0.9	1.50E-01	2.70E+02	270.15	**X**	x
1	1.30E-01	2.30E+02	230.13	**X**	x
2	5.00E-02	8.70E+01	**87.05**	**X**	x
4	1.60E-02	2.80E+01	28.016		x
6	7.40E-03	1.30E+01	13.0074		x
8	4.40E-03	7.60E+00	7.6044		x
10	2.90E-03	5.10E+00	**5.1029**		x
20	5.90E-04	1.00E+00	1.00059		
40	9.80E-05	1.70E-01	0.170098		
60	2.80E-05	5.00E-02	0.050028		
80	1.20E-05	2.10E-02	0.021012		



a) b)

Fig. 3. a) TEDE Contour Plot for the scenario described in Table 2 for wind speed 5 ms^{-1}. The dose contour values for the plume was 500 mSv (inner), 50 mSv (middle) and 5 mSv (outer); b) TEDE Contour Plot for the scenario described in Table 3 for wind speed 10 ms^{-1} wind speed (the dose contour values for the plume was 500 mSv (inner), 50 mSv (middle) and 5 mSv (outer))

The TEDE values for the release of the total amount of Uranium and Plutonium due to an explosion were comparable to those deriving from the combined model for the explosion and release from the height.

Choosing the right dispersion model (it is a choice based on the type of accident, the type of plant involved, the geographical and meteorological conditions involved) for the scenario under investigation is of extreme importance. Therefore, it would be very useful to have a background scenario to refer to. For this reason, past radiological and nuclear events represent a unique source of information which can be used, together with the atmospheric dispersion model software, to create emergency plans for the first responders in order to manage the early stages of a radiological or nuclear event.

Future developments of this work will aim at understanding if the discrepancies between the type of the release and the HotSpot diffusion model are to be attributed to the contour values chosen for the benchmark, or to the characteristics of the HotSpot models. The main goal for the future is is develop a method to give an early warning system to the first responders in order to reduce their risks in case of accidents and to give safe ways routes for the population in case of radiological and/or nuclear accidents.

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