SIMULATION OF CAESIUM-137 (^{137}Cs) LOCAL DIFFUSION AS A CONSEQUENCE OF THE CHERNOBYL ACCIDENT USING HOTSPOT

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ABSTRACT

The accident at the Chernobyl nuclear reactor in 1986 is considered as the most severe event that has ever occurred in the nuclear power industry, due to the considerable amounts of radioactive material released into the environment. The main purpose of this work is to simulate the dynamics of the local diffusion of caesium-137 (^{137}Cs) in the area strictly close to the Chernobyl reactor. Among the released radionuclides, we selected ^{137}Cs as it was responsible for most of the radiation exposure received by the general population. In order to simulate its local dispersion, HotSpot was used, being a user friendly freeware, and allowing to obtain data in terms of total effective dose equivalent (TEDE) and ground deposition. Two scenarios were simulated (General Fire and General Explosion) using boundary conditions selected from literature data. The obtained output data for the ground depositions were compared with the real ones, demonstrating that HotSpot allows for the simulation of radionuclide local release and diffusion due to the Chernobyl accident, even if only at a low scale. In fact, the relative proportions for the ground depositions values were respected and the measured TEDE values were in good agreement with the literature data.

Keywords: *Chernobyl accident; local caesium-137 (^{137}Cs) diffusion; HotSpot; total effective dose equivalent (TEDE); ground deposition.*

1. INTRODUCTION

On 26 April 1986, the most serious accident in the history of the nuclear industry occurred at the Chernobyl nuclear power plant in Ukraine, about 20 km south of the border with Belarus. This event can be considered one of the most significant nuclear accidents within the chemical biological, radiological & nuclear (CBRN) events (Bellecci *et al*., 2010; Malizia *et al*., 2010, 2011, 2012; Cenciarelli *et al*., 2013a, b; Gallo *et al*., 2013; Gaudio *et al*., 2011; Gaudio *et al*., 2013a, b; Pazienza *et al*., 2013, 2014).

Two explosions, which destroyed the core of Unit 4 and the roof of the reactor building, caused a dispersion of hot and highly radioactive debris, including fuel, core components, structural items and graphite into the air, and, at the same time, exposed the destroyed core to the atmosphere (IAEA, 2006). The plume of smoke, which contained radioactive fission products and debris, rose up to about 1 km into the air. Moreover, its duration was unexpectedly long, lasting over than ten days and presenting variable release rates. Both these factors (duration and altitude) were mainly ascribed to the graphite fire which was difficult to extinguish until Day 10, when the releases abruptly dropped and the intense release of radioactive materials stopped. The situation was further complicated by the meteorological conditions and the frequent changes of wind direction during the release period, leading to a non-uniform local contamination, either from the point of view of fallout density and radionuclide composition (IAEA, 2006).

For all these reasons, the area affected by the radioactive plume and the consequent deposition of radioactive substances on the ground were extremely large, surrounding the whole Northern hemisphere, even if significant contamination outside the former Soviet Union only involved a part of Europe. In 1988, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) provided more precise data based not only on the Soviet deposition, but also on the worldwide one (UNSCEAR, 1988; Bergichev, 1990). On the basis of later analyses related to the core debris and the deposited material within the reactor building, it was estimated that the total release of radioactive substances was about 14 EBq, including 1.8 EBq of iodine-131 (^{131}I), 0.085 EBq of caesium-137 (^{137}Cs) and other caesium radioisotopes, 0.01 EBq of strontium-90 (^{90}Sr), and 0.003 EBq of plutonium radioisotopes. Noble gases contributed about 50% of the total release of radioactivity (IAEA, 2006). The release fraction of ^{137}Cs was 20 to 40% of the core inventory (i.e., 85±26 PBq) considering an average release fraction from fuel of 47% with subsequent retention of the remainder within the reactor building (IAEA, 1986; Bedyaev *et al*., 1991; Buzulukov & Dobrynin, 1993), whereas for ^{131}I, the most accurate estimate was 50 to 60% of the core inventory (i.e., 3,200 PBq).

Among the released radionuclides, the attention was mostly focused on ^{137}Cs, being considered as a particularly dangerous fission product, due to its intermediate half-life and its properties in terms of high-energy radioactivity and chemical reactivity. Its half-life of about 30 years is long enough to yield contaminated areas dangerous to humans for a generation or more , and it is short enough to ensure that even relatively small quantities of release causes dangerous doses of radiation (its specific radioactivity is 3.2×10^{12} Bq/g) (Bunting, 1975; Unterweger *et al*., 1992; NEA-OECD, 2002). In addition, ^{137}Cs undergoes high-energy beta decay (Parekh *et al*., 2008) and, being an alkali metal, is much more chemically reactive than many of the transition metal fission products. It also readily reacts with oxygen and water (Holleman & Wiberg, 2001).

As consequence of Chernobyl explosion, cesium radioactivity followed to ground deposition of fallout particles was over $1,5 \times 10^6$ Bq/m^2 within a 30 km radius, whereas it reached 5×10^6 Bq/m^2 in the northeast Belarus (NEA-OECD, 2002), and was only 8×10^4 Bq/m^2 in southern Sweden, several hundred km northwest (and upwind) of the disaster (Devell, 1986). In 2002, 16 years after the Chernobyl disaster (about one half of the ^{137}Cs half-life), a 4,000 km^2 area was still too contaminated to be unpopulated for several more years of the remaining half-life of the released ^{137}Cs (NEA-OECD, 2002).

It would be very interesting to make simulations of the dynamics of the local diffusion of ^{137}Cs in the area strictly close to the Chernobyl reactor in order to improve our knowledge about nuclear safety and security. In this work, HotSpot (Homann & Aluzzi, 2013) was used to achieve this purpose. This software presents many advantages, since it is a user friendly freeware and allows simulation of a wide range of scenarios, considering many concomitant factors. Indeed, in the case of severe nuclear accidents, the released radioactive materials, both in the form of gases and particulates, disperse downwind as a plume, and their concentrations in the air and, after the fallout, on the soil depend on several factors, such as the amount of released radionuclide and the height of emission point. Other factors, such as wind speed, atmospheric stability, and physical and chemical forms of the released material influence the radioactivity in the environment (IAEA, 2001).

2. HOTSPOT

HotSpot Health Physics aims to provide emergency response personnel and emergency planners with a fast, field-portable set of software tools for evaluating incidents involving radioactive material. The software is also used for safety analysis of facilities handling radioactive materials. The atmospheric dispersion models used by HotSpot software are a first-order approximation of the radiation effects associated with the short-term (less than a few hours) atmospheric discharge of radioactive materials. In fact, they are designed for near-surface releases, short-range (less than 10 km) dispersion, and short-term (less than 24 h) emission in unobstructed terrains and simple meteorological conditions. HotSpot estimates the dispersal of radioactive material using the Gaussian model, since the adequacy of this model for making initial dispersion estimates or worst-case safety analyses has been tested and verified for many years (Homann & Aluzzi, 2013).

The HotSpot codes are continuously updated to incorporate the most current and approved radiological dose conversion data and methodologies. These codes are based on the well established Gaussian plume model (GPM), widely used for an initial emergency assessment or safety analysis planning of a radionuclide release. The main advantages of GPM are short computation time, extensive validation and worldwide acceptance. Virtual source terms are used to model the initial 3D distribution of material associated with an explosive or fire release, resuspension, or user-input geometry (Homann & Aluzzi, 2013). For evaluation of radiological scenarios, HotSpot uses the methods of radiation dosimetry recommended by the International Commission on Radiological Protection (ICRP) (ICRP, 2005) and US Environmental Protection Agency's (EPA) Federal Guidance Reports No. 11, 12 and 13 (EPA, 1988, 1993, 1999).

3. METHODOLOGY

For the simulation of the radionuclide dispersion during the Chernobyl accident, two different scenarios were applied (General Fire and General Explosion), taking into account that this event was characterised by two explosions and the graphite fire. Among the several involved radionuclides, we decided to study the dispersion of ^{137}Cs, since it was the main radionuclide responsible of exposure to the population. Moreover, another main purpose of this work was to evaluate its dispersion within the first hour from the beginning of the accident, according to the features of the software. All the parameters used were identified from literature data (Apsimon, 1985; IAEA, 2006). The selected boundary conditions are summarised in Table 1.

For the source term, the following values were selected: material at risk (MAR), 25 PBq (amount released on the first day (i.e., 26 April 1986)); damage ratio (DR), 1.00; leakpath factor, 1.00; airborne fraction (ARF), 1.00; and respirable fraction (RF), 1.00; and deposition velocity, 0.15 cm/s (Apsimon, 1985; IAEA, 2006). Specifically, in the case of the General Fire scenario, the cloud top was set as 900 m , since it was reported that the plume rose up to about 1 km into the air during the first hours (the software does not allow for the selection of a cloud top value higher than 900 m). For the General Explosion scenario, all the parameters were maintained unaltered, adding for high explosive a value of 10 t (22,000 lb), since the nuclear excursion released 40 bil. J of energy, which is the equivalent of about 10 t of trinitrotoluene (TNT) (Pakhomov & Dubasov, 2010).

Finally, the boundary conditions were selected, in terms of total effective dose equivalent (TEDE) and ground deposition (soil radioactivity value in kBq/m^2). For TEDE, the inner, middle and outer parameters were set up as 5 Sv (threshold for immediate deterministic effects), 20 mSv (maximum dose for first responders) and 1 mSv (operational level for evacuation) respectively (ICRP, 1996). Values of 2,000, 1,000 and 350 kBq/m^2 were chosen for the ground deposition inner, middle and outer parameters respectively on the basis of literature data, considering the area close to the Chernobyl district. In fact, four main ^{137}Cs contamination ranges (i.e., 37-185 kBq/m^2, 185-555 kBq/m^2, 555-1,480 kBq/m^2 and > 1,480 kBq/m^2) were reported and identified (IAEA, 2006) and, thus, in this simulation the three highest contamination level ranges were considered, employing the average values.

4. RESULTS & DISCUSSION

The HotSpot outputs for the General Fire and General Explosion scenarios are reported in Table 2. Figures 1 and 2 show the graphical representations of the results for both the simulated scenarios, in terms of ground deposition isoconcentration and TEDE isodose respectively, in a Cartesian system with the *x*-axis oriented in the main wind direction.

Table 1: Boundary conditions for the General Fire and General Explosion scenarios.

	Parameter	Value	
Source term characteristics	Source material	^{137}Cs	30.0 y
	Material at risk (Bq)	25.0×10^{15}	
	Deposition velocity (cm/s)	0.15	
	Damage ratio	1.0	
	Leakpath factor	1.0	
	Airborne fraction (ARF)	1.0	
	Respirable fraction (RF)	1.0	
General Fire scenario			
Fuel fire information	Physical height of the fire (m)	10.0	
	Release radius (m)	30.0	
	Cloud top (m)	900.0	
	Effective release height (m)	309.0	
	Wind speed (*height*=10 m) (m/s)	10.0	
	Distance coordinates	All distances are on the plume centreline	
General Explosion scenario			
Explosive	High explosive (lb)	2.2×10^4	
Meteorological conditions	10 m wind speed (m/s)	10.0	
	Wind direction	175.0° (wind from south)	
	Stability class	A	
	Atmospheric stability (actual stability)	very unstable	
	Non-respirable deposition velocity (cm/s)	8.0	
	Receptor height	1.5 m	
	Inversion layer height	None	
	Sample time (min)	10.0	
	Wind ref. Height (m)	10.0	
	Breathing rate (m^3/s)	$3.3 \text{ x } 10^{-4}$	
TEDE (Sv)	Inner contour dose	5.0	
	Middle contour dose	20.0×10^{-3}	
	Outer contour dose	1.0×10^{-3}	
Deposition (kBq/m^2)	Inner	2000.0	
	Middle	1000.0	
	Outer	350.0	

The ground deposition contour plots highlight the maximum distances of deposition curves from the zero point (hotspot) downwind. Comparing the obtained areas (3.4, 8.6 and 29.0 km^2 for the General Fire scenario; 2.4, 6.8 and 25.0 km^2 for the General Explosion scenario), it was evident that they were remarkably lower with respect to the real ones (600, 900 and 3,200 km^2) (IAEA, 2006), as expected. HotSpot allows for the simulation of radionuclide atmospheric dispersion, providing reliable and significant data for up to only about 10 km from the reactor site. However, it is interesting to note that the ratios between the considered areas were comparable for the General Fire and General Explosion scenarios with respect to the real data, as reported in Table 3. This experimental evidence suggests, and further validates, that the HotSpot code is able to simulate the ^{137}Cs release due to Chernobyl accident at a low scale.

The measured TEDE values showed that the selected conditions were not able to induce a deterministic hazard, since the related threshold (i.e., 5 Sv) was not overcome. However, the simulation revealed the presence of areas with TEDE values higher than 20 mSv up to maximum distances between around 4.3 and 7.7 km, on the basis of the considered scenarios, suggesting the need of an immediate area evacuation. Moreover, considering the outer area, which measured approximately 216-244 km^2, it could be inferred that a maximum distance of around 45-50 km from hot spot would impart a TEDE of at least 1 mSv, even if it has to be taken into account that the HotSpot data can be considered as reliable for only within 10 km.

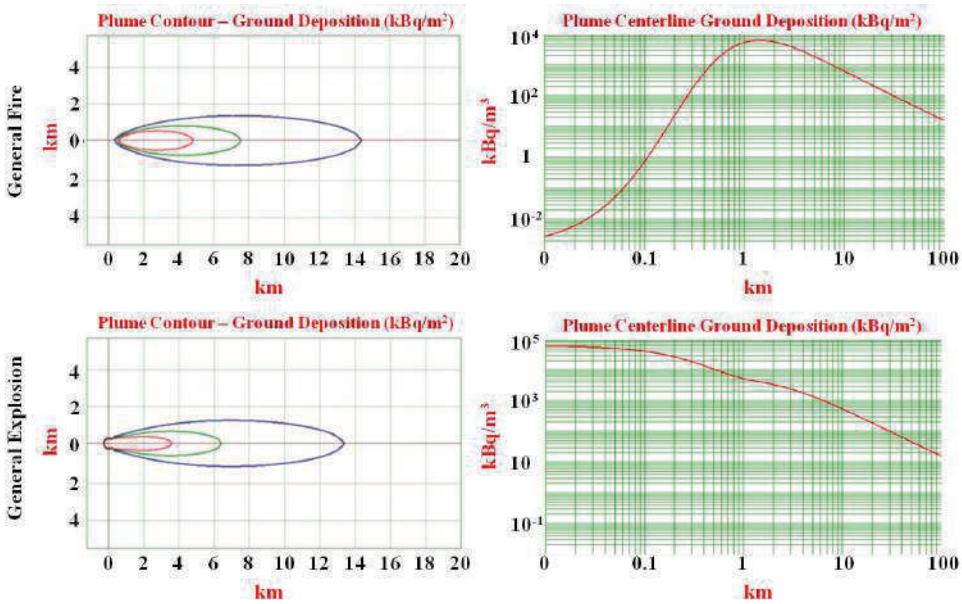

Figure 1: Ground deposition isoconcentration as a function of distance.

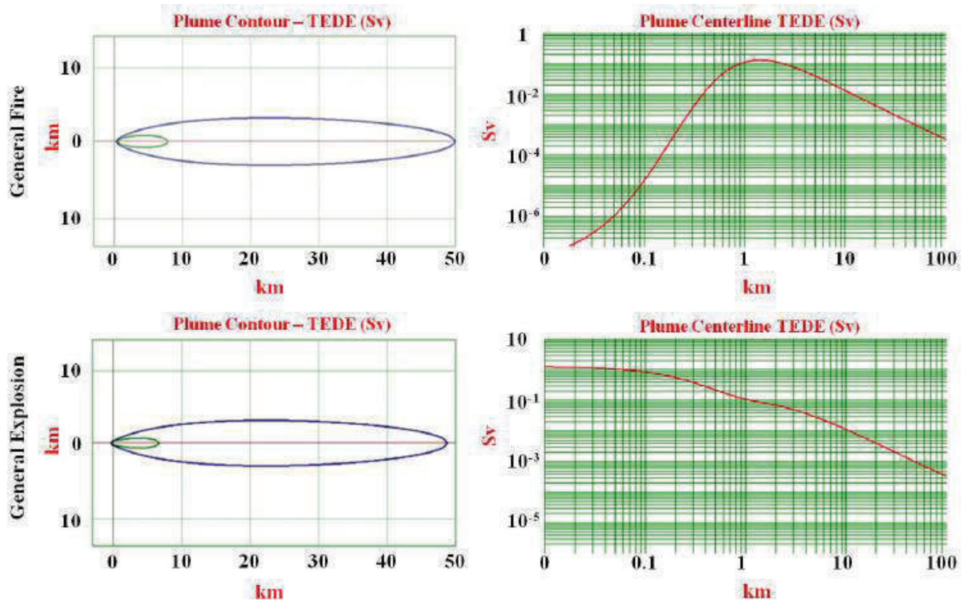

Figure 2: TEDE isodose as a function of the distance.

The output data obtained from General Fire scenario simulation fitted well with the data from the literature, since it was reported that the average effective doses were around 100 mSv for the liquidators (highly exposed), 50 mSv for the residents in strictly controlled zones (SCZs, where radioactive caesium contamination exceeded 555 kBq/m^2) and 30 mSv for the evacuees. In fact, a maximum TEDE value of 131 mSv was detected at 1.4 km from the release point, whereas TEDE values in the range 30-55 mSv were revealed between 4 and 8 km (that could be considered the SCZs in this low scale simulation). Moreover, in the case of General Explosion setup, remarkably higher maximum effective dose values (i.e. 1.3 Sv) were detected at around 0.01 km (very close to the release point), corroborating the very high values revealed in the area were strictly close to the reactor. In Table 4, the measured distances for the maximum TEDE values for the deterministic effects threshold and for several well-known Operational Intervention Levels (OILs) are reported for all the considered scenarios.

Table 2: HotSpot outputs for the General Fire (GF) and General Explosion (GE) scenarios.

Distance (km)	TEDE (Sv)		Respirable time-integrated air concentration ((Bq-sec)/m^3)		Ground surface deposition (kBq/m^2)		Ground shine dose rate (Sv/h)		Time (h:min)	
	GF	GE	GF	GE	GF	GE	GF	GE	GF	GE
0.03	2.80E-07	1.20E+00	8.9E+03	3.70E+10	1.3E-02	5.50E+04	2.6E-09	1.1E-02	<00:01	<00:01
0.1	1.50E-05	8.50E-01	4.9E+05	2.70E+10	7.3E-01	4.00E+04	1.5E-07	8.1E-03	<00:01	<00:01
0.2	4.80E-04	5.60E-01	1.5E+07	1.80E+10	2.2E+01	2.70E+04	4.5E-06	5.3E-03	<00:01	<00:01
0.3	3.50E-03	3.90E-01	1.1E+08	1.20E+10	1.7E+02	1.80E+04	3.3E-05	3.7E-03	<00:01	<00:01
0.4	1.20E-02	2.90E-01	3.8E+08	9.00E+09	5.7E+02	1.40E+04	1.1E-04	2.7E-03	<00:01	<00:01
0.5	2.70E-02	2.20E-01	8.5E+08	7.00E+09	1.3E+03	1.10E+04	2.5E-04	2.1E-03	<00:01	<00:01
0.6	4.60E-02	1.80E-01	1.4E+09	5.70E+09	2.2E+03	8.60E+03	4.3E-04	1.7E-03	<00:01	<00:01
0.7	6.60E-02	1.50E-01	2.1E+09	4.80E+09	3.1E+03	7.30E+03	6.2E-04	1.5E-03	<00:01	<00:01
0.8	8.50E-02	1.30E-01	2.7E+09	4.20E+09	4.0E+03	6.30E+03	8.0E-04	1.3E-03	00:01	<00:01
0.9	1.00E-01	1.20E-01	3.2E+09	3.80E+09	4.7E+03	5.70E+03	9.5E-04	1.1E-03	00:01	00:01
1	1.10E-01	1.10E-01	3.6E+09	3.50E+09	5.3E+03	5.20E+03	1.1E-03	1.0E-03	00:01	00:01
2	1.20E-01	7.10E-02	3.7E+09	2.20E+09	5.5E+03	3.30E+03	1.1E-03	6.7E-04	00:02	00:02
4	5.50E-02	3.70E-02	1.7E+09	1.20E+09	2.6E+03	1.80E+03	5.2E-04	3.5E-04	00:05	00:04
6	3.00E-02	2.30E-02	9.5E+08	7.20E+08	1.4E+03	1.10E+03	2.8E-04	2.2E-04	00:07	00:07
8	1.90E-02	1.60E-02	6.0E+08	4.90E+08	9.0E+02	7.40E+02	1.8E-04	1.5E-04	00:10	00:09
10	1.30E-02	1.10E-02	4.2E+08	3.60E+08	6.3E+02	5.30E+02	1.3E-04	1.1E-04	00:13	00:12
20	4.30E-03	4.00E-03	1.4E+08	1.30E+08	2.0E+02	1.90E+02	4.1E-05	3.7E-05	00:26	00:24
40	1.40E-03	1.40E-03	4.5E+07	4.30E+07	6.7E+01	6.40E+01	1.3E-05	1.3E-05	00:52	00:49
60	7.50E-04	7.30E-04	2.4E+07	2.30E+07	3.5E+01	3.40E+01	7.1E-06	6.9E-06	01:18	01:13
80	4.80E-04	4.70E-04	1.5E+07	1.50E+07	2.3E+01	2.20E+01	4.5E-06	4.4E-06	01:44	01:38

Table 3: Comparison between real and simulated ground deposition areas.

		Ground deposition (kBq/m^2)			Relative Proportions
		Inner (2,000)	Middle (1,000)	Outer (350)	
Area (km^2)	HotSpot ground deposition (General Fire)	3.4	8.6	29.0	0.12:0.30:1.00
	HotSpot ground deposition (General Explosion)	2.4	6.8	25.0	0.10:0.27:1.00
	Ukraine areas contaminated (IAEA, 2006)	600.0	900.0	3,200.0	0.19:0.28:1.00

The defined OILs, in terms of avertable doses by implementing protective measures, are (ICRP, 1996): OIL1, dose rate in radioactive plume = 1.0 mSv/h, evacuation or substantial sheltering in the affected 22.5° angular sector and the two adjacent sectors; OIL2, dose rate in radioactive plume = 0.1 mSv/h, thyroid blocking agent administration and sheltering with windows closed; OIL3, environmental dose rate in deposition = 1 mSv/h, evacuation and substantial sheltering in the affected sector; OIL4, environmental dose rate in deposition = 0.2 mSv/h, population relocation from the affected sector; and OIL5, environmental dose rate in deposition = 1 μSv/h, immediate restriction of food and milk consumption (potentially contaminated) from the affected sector until samples are analysed.

Table 4: Measured distances (km) for the maximum TEDE values, deterministic effects threshold and for several well-known Operational Intervention Levels (OILs).

Parameters		General Fire	General Explosion
Maximum TEDE value (Sv)		0.131	1.3
Maximum dose distance (km)		1.4	0.01
Deterministic effects threshold exceeding area		No exceeding	No exceeding
Exceeding area (km^2)	OIL1	50.0	49.0
	OIL2	-	-
	OIL3	1.0-2.0	1.0
	OIL4	10.0	6.0
	OIL5	-	-

Finally, HotSpot allows for the display of contours for both ground deposition and TEDE at the release location in Google Earth, inserting the Chernobyl reactor geographical coordinate (i.e., 51.38955 N, 30.09915 E). In Figure 3 the georeferencing of TEDE isodoses and ground deposition isoconcentrations are shown, indicating the areas affected by ^{137}Cs dispersion.

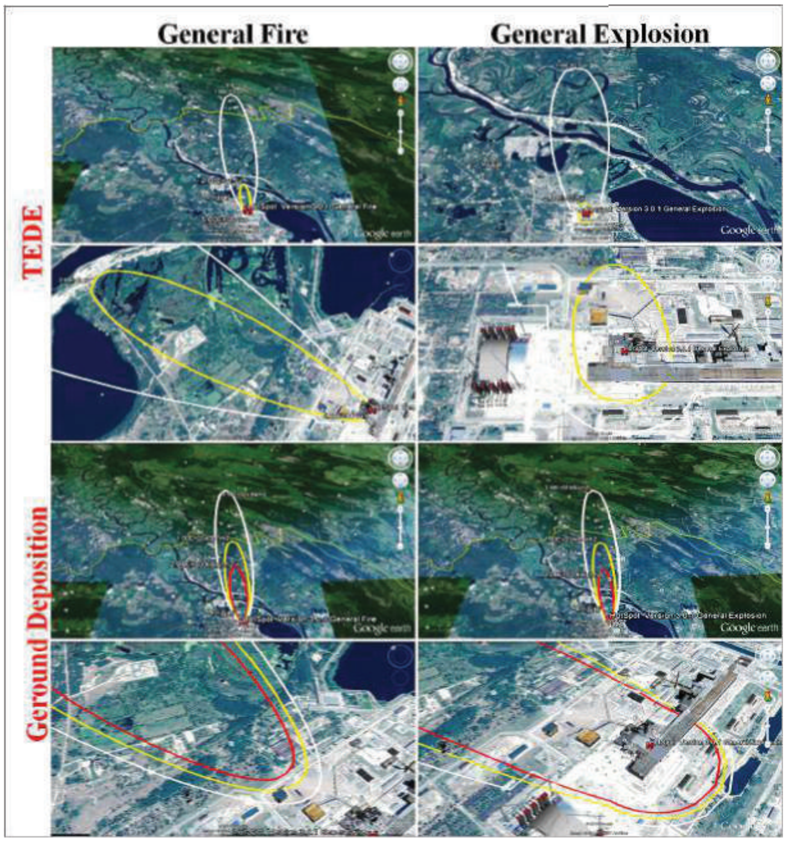

Figure 3: Georeferencing of TEDE and ground deposition data.

5. CONCLUSION

The ^{137}Cs air dispersion as a consequence of Chernobyl accident was simulated using HotSpot. Through comparison of the obtained output data for the ground depositions with the real ones, it was found that the relative proportions for the ground depositions values were respected and the measured TEDE values were in good agreement with the literature data. Thus, it is possible to conclude that HotSpot code allows for the simulation of radionuclide local release and diffusion. Nevertheless, its limitations is that it is only designed for near-surface releases, short-range (less than 10 km) dispersion and short-term (less than 24 h) release durations in unobstructed terrains and simple meteorological conditions.

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REFERENCES

Apsimon, H.M., Goddard, A.J.H., Wrigley, J. & Crompton, S. (1985). Long-range atmospheric dispersion of radioisotopes-ii, application of the MESOS model. *Atmos. Environ.*, **19**:113-125.

Bedyaev, S.T., Borovoi, A.A., & Demin, V.F. (1991). The Chernobyl source term. *Proc. Seminar on Comparative Assessment of the Enviromental Impact of Radionuclides Released during Three Major Nuclear Accidents: Kyshtym, Windscale, Chernobyl*, EVR-13574, CEC, pp. 71-91.

Bellecci, C., Gaudio, P., Gelfusa, M., Malizia, A., Richetta, M., Serafini, C. & Ventura, P. (2010). Planetary boundary layer (PBL) monitoring by means of two laser radar systems: experimental results and comparison. *Proc. SPIE*, **7832**: 78320X.

Bergichev, S.N. (1990). Radioactive releases due to the Chernobyl accident. *In* Rogers, J.T. (Ed.), *Fission Product Transport Processes in Reactor Accidents*. JT Rogers, editor, Hemisphere Publishing, London.

Bunting, R. L. (1975). Nuclear data sheets for A= 137. *Nucl. Data Sheet.*, **15**: 335-369.

Buzulukov, Y.P. & Dobrynin, Y.L. (1993). Release of radionuclides during the Chernobyl accident. *Chernobyl Pap.*, **1**:3-21.

Cenciarelli, O., Malizia, A., Marinelli, M., Pietropaoli, S., Gallo, R., D'Amico, F., Bellecci, C., Fiorito, R., Gucciardino, A. & Gaudio, P. (2013a). Evaluation of biohazard management of the Italian national fire brigade. *Defence S&T Tech. Bull.*, **6**:33-41.

Cenciarelli, O., Rea, S., Carestia, M., D'Amico, F., Malizia, A., Bellecci, C., Gaudio, P., Gucciardino, A. & Fiorito, R. (2013b). Bioweapons and bioterrorism: A review of history and biological agents. *Defence S&T Tech. Bull.*, **6**: 111-129.

Devell, L., Tovedal, H., Bergström, U., Appelgren, A., Chyssler, J. & Andersson, L. (1986). Initial observations of fallout from the reactor accident at Chernobyl. *Nature*, **321**:192-193.

EPA (Environmental Protection Agency) (1988). *Federal Guidance Report No. 11: Limiting Values Radionuclide Intake and Air Concentration, and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*. Environmental Protection Agency (EPA), Washington DC, USA.

EPA (Environmental Protection Agency) (1993). *Federal Guidance Report No. 12: External Exposure to Radionuclides in Air, Water, and Soil*. Environmental Protection Agency (EPA), Washington DC, USA.

EPA (Environmental Protection Agency) (1999). *Federal Guidance Report No. 13: Cancer Risk Coefficients for Environmental Exposure to Radionuclides*. Environmental Protection Agency (EPA), Washington DC, USA.

Gallo, R., De Angelis, P., Malizia, A., Conetta, F., Di Giovanni, D., Antonelli, L., Gallo, N., Fiduccia, A., D'Amico, F., Fiorito, R., Richetta, M., Bellecci, C. & Gaudio, P. (2013). Development of a georeferencing software for radiological diffusion in order to improve the safety and security of first responders. *Defence S&T Tech. Bull.*, **6**: 21-32.

Gaudio, P., Gelfusa, M., Lupelli, I., Malizia, A., Moretti, A., Richetta, M., Serafini, C. & Bellecci, C. (2011). First open field measurements with a portable CO_2 lidar/dial system for early forest fires detection. *Proc. SPIE*, **8182**: 818213.

Gaudio, P., Gelfusa, M., Malizia, A., Richetta, M., Antonucci, A., Ventura, P., Murari, A. & Vega, J. (2013a). Design and development of a compact lidar/DIAL system for aerial surveillance of urban areas. *Proc. SPIE*, **8894**: 88940D.

Gaudio, P., Gelfusa, M., Malizia, A., Richetta, M., Serafini, C., Ventura, P., Bellecci, C., De Leo, L., Lo Feudo, T. & Murari, A. (2013b). New frontiers of Forest Fire Protection: A portable Laser System (FfED). *WSEAS Tran. Environ. Dev.*, **9**: 195-205.

Holleman, A.F. & Wiberg, E. (2001). *Inorganic Chemistry*. Academic Press, London, UK.

Homann, S.G. & Aluzzi, F. (2013). *HotSpot Health Physics Codes Version 3.0 User's Guide*. National Atmospheric Release Advisory Center Lawrence Livermore National Laboratory, Livermore, California, USA.

IAEA (International Atomic Energy Agency) (1986). *Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident.* Safety Series No. 75-INSAG-1*,* International Atomic Energy Agency (IAEA), Vienna, Austria.

IAEA (International Atomic Energy Agency) (2001). *Generic Models for use in assessing the impact of discharges of radioactive substances to the environment.* Safety Series No. 9*,* International Atomic Energy Agency (IAEA), Vienna, Austria.

IAEA (International Atomic Energy Agency) (2006). *Environmental consequences of the Chernobyl accident and their remediation: twenty years of experience / report of the Chernobyl, Forum Expert Group "Environment",* International Atomic Energy Agency (IAEA) International Atomic Energy Agency (IAEA) International Atomic Energy Agency (IAEA), Vienna, Austria.

International Commission on Radiological Protection (ICRP) (1996). *Basic Anatomical & Physiological Data for use in Radiological Protection: The Skeleton*. ICRP publication 70, ICRP, Elsevier, United Kingdom.

International Commission on Radiological Protection (ICRP) (2005). *Basis for Dosimetric Quantities Used in Radiological Protection*. ICRP, Ottawa, Canada.

Malizia, A., Quaranta, R. & Mugavero, R. (2010). CBRN events in the subway system of Rome: Technical-managerial solutions for risk reduction. *Defence S&T Tech. Bull.*, **3**:140-157.

Malizia, A., Quaranta, R., Mugavero, R., Carcano, R., & Franceschi, G. (2011). Proposal of the prototype RoSyD-CBRN, a robotic system for remote detection of CBRN agents. *Defence S&T Tech. Bull.*, **4**:64-76.

Malizia, A., Lupelli, I., D'Amico, F., Sassolini, A., Fiduccia, A., Quarta, A. M., Fiorito, R., Gucciardino, A., Richetta, M., Bellecci, C. & Gaudio, P. (2012). Comparison of software for rescue operation planning during an accident in a nuclear power plant. *Defence S&T Tech. Bull.*, **1**:36-45.

NEA-OECD (Nuclear Energy Agency of the Organization for Economic Cooperation and Development) (2002). *Chernobyl: Assessment of Radiological and Health Impacts*. Available online at: http://www.oecd-nea.org/rp/chernobyl (Last access: 15 February 2014).

Pakhomov, S.A. & Dubasov, Y.V. (2010). Estimation of explosion energy yield at Chernobyl NPP accident. *Pure Appl. Geophys.*, **167**:575-580.

Parekh, N.R., Poskitt, J.M., Dodd, B.A., Potter, E.D., Sanchez A. (2008). Soil microorganisms determine the sorption of radionuclides within organic soil systems. *J. Environ. Radioactiv.*, **99**: 841–852.

Pazienza, M., Britti, M.S., Carestia, M., Cenciarelli, O., D'Amico, F., Malizia, A., Bellecci, C., Gaudio, P., Gucciardino, A., Bellino, M., Lancia, C., Tamburrini, A. & Fiorito, R. (2013). Application of real-time PCR to identify residual bio-decontamination of confined environments after hydrogen peroxide vapor treatment: Preliminary Results. *J. Microb. Biochem. Technol.*, **6**: 24-28.

Pazienza, M., Britti, M.S., Carestia, M., Cenciarelli, O., D'Amico, F., Malizia, A., Bellecci, C., Fiorito, R., Gucciardino, A., Bellino, M., Lancia, C., Tamburrini, A. & Gaudio, P. (2014). Use of particle counter system for the optimization of sampling, identification and decontamination procedures for biological aerosols dispersion in confined environment. *J. Microb. Biochem. Technol.*, **6**: 43-48.

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) (1988). *Sources, Effects and Risks of Ionizing Radiation.* Report to the United Nations, United Nations Scientific Committee on the Effects of Atomic Radiation (UNESCAR), New York, USA.

Unterweger, M. P., Hoppes, D. D. & Schima, F. J. (1992). New and revised half-life measurements results. *Nucl. Instrum. Meth. A*, **312**:349-352.