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Simulation of the Radioactive Release of ^{90}Sr from a Hypothetical Severe Accident in a Nuclear Power plant for Use as a Possible Decision Support System (DSS)

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ABSTRACT

These days, one of the most important safety and security concerns of the new century is the use of Decision Support Systems, such as software to assist specialists during emergency preparedness operations in the event of an atypical incident (such as a radioactive diffusion). Natural or man - made accident that have a detrimental effect on the environment and public health. The DSS is required to enhance the prevention phase, which is important in an emergency preparedness system, as well as to ensure that the right safety route is chosen to promote the safety of operators and the populace in the event of a disaster. The HOT SPOT code, a free license code, was utilized in this work to model radioactive accident scenarios. The ^{90} Sr contamination was chosen to simulate a worst-case scenario. It is an accident because the release of ^{90} Sr (28.8 years) into the environment following a nuclear accident can have detrimental long-term effects on the ecosystem and human health. It can contaminate soil, water, and living things in the environment for decades. Its radioactive beta emissions, which can cause leukemia, bone cancer, and other illnesses, are the main health hazards. Because of its similarity to calcium, it is readily absorbed by bones, putting both humans and animals at danger for long-term radiation exposure. Public safety, environmental monitoring, and pollution remediation are the main areas of focus for efforts to reduce these risks. The radioactive diffusion caused by an accident has been simulated using the HOT SPOT algorithm. In order to determine the actual viability of using HOT SPOT as DSS during the prevention and/or intervention emergency phases, this paper analyzes and discusses the scenario used in the simulation to evaluate its spread from data for the Total Effective Dose (TEDE) and the deposition of material on the ground , the results showed that maximum Total Effective Dose Equivalent (TEDE) occurred within the first kilometer from the source (0.19–0.28 Sv), with ground deposition peaking at 0.2–0.6 km (2.6×10^4–3.8×10^4 kBq/m^2).

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Introduction

Health, safety, homeland and national security, socioeconomic situations, and the environment could all be significantly impacted by the radionuclides discharged by the nuclear power station NPP in the event of a hypothetical severe accident (Mohamed *et al.*, 2012). In order to respond correctly and prevent disasters, it is important to explain and understanding how, where, and when these materials are transported, dispersed, and deposited in the atmosphere. Determining the causes of harmful accident releases enables decision-makers to create focused plans and policies to lessen the issue (An *et al.*, 2016). For the investigation of a hypothetical NPP accident, radiological consequence analysis could be studied and predicted (Musauddin and Kim, 2019). To determine the dangers to the environment and people, it would be helpful to analyze NPP incidents. Additionally, future nuclear power plant accident prediction and estimation are important because they can support emergency plans in the event of a hypothetical accident (UNSCEAR, Volume II, Annex J, 2000). Additionally, after NPP accidents, radioactive elements released into the atmosphere may spread throughout the air and land on the earth (IAEA, Safety Reports Series 19, Vienna, 2001). Different factors affecting these dispersal processes include speed of wind, directions of wind, atmospheric stability, surrounding temperatures (see Fig.1), and so on. All these factors can contribute to the severity of a particular accident in general and vary in term of damage to the public (Voigt *et al.*, 2009). The main objective of this research to investigate the atmospheric dispersion and radiological risk to the public around NPP under hypothetical accidents and show how the HotSpot program may be used as a Decision Support System (DSS) in emergency planning and how it can simulate radioactive contamination caused by the spread of radioactive materials in an area close to an accident site.

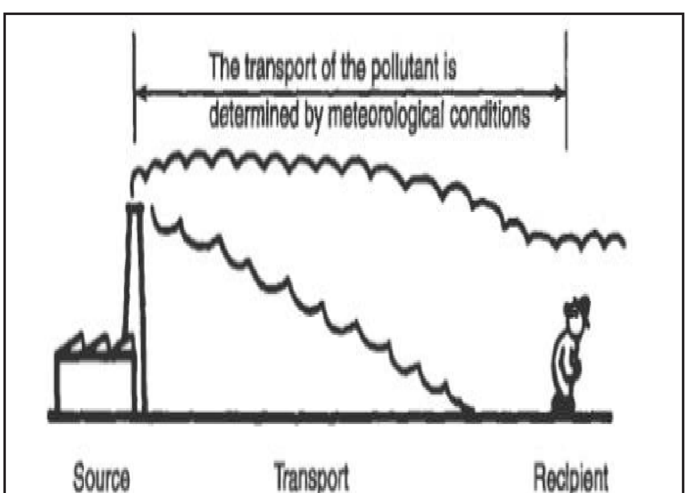

Figure (1): Meteorology of air pollutants

Materials and methods

HotSpot is a free license code that provides a fast method to evaluate the radiation effects associated with the atmospheric release of HotSpot is a free license code that provides a fast method to evaluate the radiation effects associated with the atmospheric release of HotSpot code is a free license code that provides a quick way to assess the radiation consequences of radioactive material releases into the atmosphere. It is based on a Gaussian model that calculates the short-term (less than a few hours) and short-range (less than 10 km) predictions for the radiological impact downwind after radioactive materials are released. It is based on a Gaussian model that calculates the short-term (less than a few hours) and short-range (less than 10 km) forecasts for the radiological impact downwind after radioactive material is released. The time-integrated atmospheric pressure is calculated using the Gaussian model, and the code estimates are conservative (Carestia *et al.*, 2016). The activity of the source term involved in the scenario and the meteorological data, including the wind direction and velocity as well as the solar insolation factor, are the fundamental parameters that the model requires. Meteorologists can categorize the local atmosphere into A, B, C, D, E, and F states using these data to derive the appropriate Pasquill's stability class. These states can be calculated using the time of day, wind speed, and weather. Depending on the stability class, the attack could have a range of harmful outcomes. Therefore, just like war strategists do, the potential terrorist will surely evaluate factors to enhance the harmful effects (Carestia *et al.*, 2016 and Homann, 2011). The output produced the ground contamination expressed in kBq·m-2 as well as the committed effective dose equivalent (USNRC, 2013a) for internal exposures and the total effective dose equivalent (TEDE) expressed in Sievert (Sv) as defined in USNRC (2013b) for external exposures. HotSpot enables the user to simulate the release of any radionuclide contained in the ICRP 30 (ICRP, 1979) and ICRP 60+ (ICRP, 1991 and ICRP, 1992) because the model was created for both general releases of radionuclides and nuclear events. The TEDE contour plots and Ground Deposition contour plots, which display the downwind and crosswind contours for dose levels and the extent of the deposition, respectively, as well as the TEDE graph and Ground Deposition graph, which show the relative values as a function of plume centerline downwind distance, can also be viewed by the user using the HotSpot software. The boundary condation (ICRP, Ottawa, Canada, 2005), where the radioactive dispersion during the incident was simulated using two alternative scenarios (General plume) (EPA, Federal Guidance Report 11, Washington DC, 1988). We decided to look at the dispersion of Sr-90 as it was the main radionuclide that exposed the populace (Rentai, 2011) and

(Gallo *et al*., 2013). Furthermore, the main objective of this work was to evaluate its dispersion based on the software's capabilities during the first hour after the accident. An overview of the selected boundary conditions is given in Tables (1, 2) (Homann and Aluzzi, 2013). To simulate the ideal situation for a radioactive leak from a chimney, the "General Plume" model was selected. The basic boundary criteria were then added to the GUI (Graphical User Interface) of the software (see Figure 2) (Anvari and Safarzadeh, 2012 and Dahia *et al*., 2018).

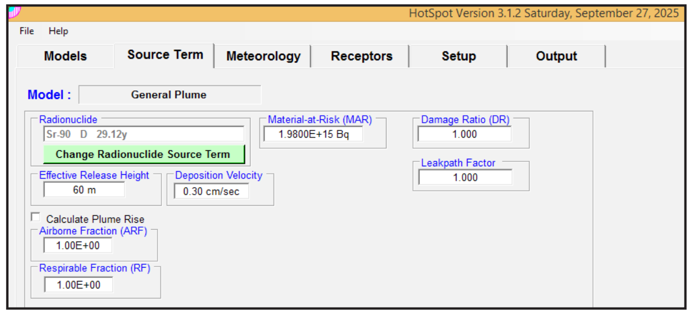

Figure (2): Source term condition

The accident scenarios simulated have been two. In tables (1,2) are reported the two different stability class:

Table 1. Boundary conditions for A stability class

Parameter	Value	
Material-at-Risk (MAR):	1.9800E+15 Bq	
Damage Ratio (DR)	1	
Airborne Fraction (ARF)	1	
Respirable Fraction (RF)	1	
Leakpath Factor (LPF)	1	
Respirable Source Term	1.98E+15 Bq	
Non-respirable Source Term	0.00E+00 Bq	
Effective Release Height	60 m	
Speed of Wind (h=10 m)	8.00 m/s	
Direction of Wind	80.0 degrees	Wind from the East
Speed of Wind (h=H-eff)	9.07 m/s	
Stability Class	A	
Respirable Dep. Vel.	0.30 cm/s	
Non-respirable Dep. Vel.	0.30 cm/s	
Receptor Height	1.5 m	
Inversion Layer Height	None	
Sample Time	30.000 min	
Breathing Rate	3.33E-04 m3/s	
Distance Coordinates	All distances	are on the Plume Centerline

Table 2. Boundary conditions for D stability class

Parameter	Value	
Material-at-Risk (MAR):	1.9800E+15 Bq	
Damage Ratio (DR)	1	
Airborne Fraction (ARF)	1	
Respirable Fraction (RF)	1	
Leakpath Factor (LPF)	1	
Respirable Source Term	1.98E+15 Bq	
Non-respirable Source Term	0.00E+00 Bq	
Effective Release Height	60 m	
Speed of Wind (h=10 m)	3.00 m/s	
Direction of Wind	80.0 degrees	Wind from the East
Speed of Wind (h=H-eff)	3.93 m/s	
Stability Class	D	
Respirable Dep. Vel.	0.30 cm/s	
Non-respirable Dep. Vel.	0.30 cm/s	
Receptor Height	1.5 m	
Inversion Layer Height	None	
Sample Time	30.000 min	
Breathing Rate	3.33E-04 m3/s	
Distance Coordinates	All distances	are on the Plume Centerline

In all scenarios, the sample time is set at 30 minutes, and the emission point is 10 meters high. Particle resuspension and reflection on the ground can be included by using the FGR 11 DFC library (IAEA, General Safety Requirements Part 3 (2014)). The Breathing Rate at 3.33 x 10-4 m3/s for a population with medium intensity activities (Malek *et al.*, 2012). The TEDE (Total Effective Dose Equivalent) data, which represent the total equivalent dose for each organ in the body (both for internal and external deposition), have been combined with the radioactivity levels on the ground (see Fig. 3) (Homann and Aluzzi, 2020). Three different bands—internal, medium, and external—that are graphically depicted as three distinct plume zones in the polluted zone are expected by the boundary conditions (Gaudio *et al.*, 2010; Junxiao *et al.*, 2016 and ICRP, 2000). The values of greatest interest for an investigation of radioactive particle contamination are the TEDE and the ground deposition (Hawley and Kathren, 1982; ICRP Publication 72, 1995 and Anvari and Safarzadeh, 2012).

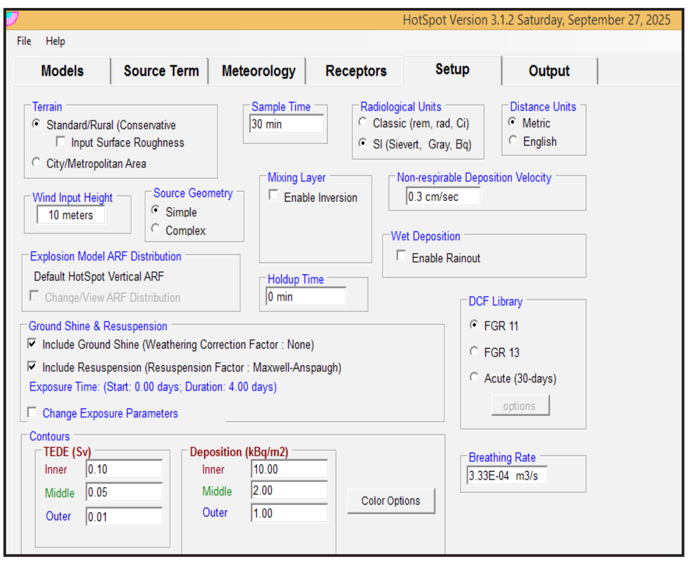

Figure (3): Setup Condition of Hot Spot

Results and Discussion

Results of Accident (Scenario 1)

Fig. (4) 30-minute plume (Scenario 1), This graphic, which was created using HotSpot at a release height of 1.5 m, depicts the radiological plume dispersion pattern 30 minutes after the discharge. The concentration contours show how radioactive material (Bq•s/m^3) spreads with downwind distance (Homann and Aluzzi, 2020). The "hotspot" area, where exposure danger is highest, is indicated by the red zone, which represents the highest concentration region close to the release point. As the plume disperses and dilutes with distance, the concentrations in the green and blue zones decrease. The elliptical shape of the plume, which spreads mostly down the wind direction with little crosswind diffusion and where radionuclide concentration rapidly drops with distance due to atmospheric mixing and dilution, illustrates how wind and atmospheric stability effect the dispersion (Gaudio *et al.*, 2010).

Figure (5): Variation of TEDE (in Sv) from the Release Point (Height = 1.5 m), The Total Effective Dose Equivalent (TEDE) is plotted against the distance downwind from the discharge location in this graph. The TEDE curve gradually decreases after rising significantly close to the source and reaching a maximum value at about 0.3–0.5 km. Before dilution takes over, this peak indicates the place where airborne concentration is high enough to result in the most inhalation and external exposure. The TEDE quickly decreases when the plume disperses after one kilometer. This curve's form is typical of short-term releases: a sharp rise brought on by high near-field concentrations, then a gradual decrease as the dose decreases with distance due to dilution and deposition (Junxiao *et al.*, 2016).

Figure (6): Deposition on the Ground (kBq/m2) Variation from the Release Point (Ground Level) displays the radioactive deposition pattern on the ground surface as a function of distance. Near the release site, deposition rises significantly and peaks between 0.1 and 0.3 km before progressively declining downwind. This tendency illustrates how tiny particles stay in the air longer and deposit farther away, whereas bigger particles and aerosols settle quickly close to the source. The findings show that the primary fallout or contaminated zone is a small area of high ground contamination close to the origin (ICRP Publication 72, 1995).

Table (3) show how the maximum exposure and contamination happen near the source (within the first kilometer) during a brief near-ground distance from the release source (0.03–80 km). TEDE (Sv) is the total effective dose equivalent received from inhalation and external exposure. TEDE confirms the greatest exposure zone around the source, peaking between 0.3 and 0.5 km (0.19 and 0.09 Sv). TEDE drastically decreases after about 2 km because of plume dilution. Similar trends are seen in air concentration (Bq•s/m^3), which is very high close to the source ($\sim10^{o}$ Bq•s/m^3) and decreases with distance. This illustrates how, as the plume travels, radionuclide density decreases (ICRP, 1995). Ground surface deposition (kBq/m^2) illustrates the accumulation of deposited activity on the ground. Where the contamination is most severe, the readings are highest between 0.1 and 0.5 kilometers. The radiation dose rate from deposited materials is called the ground shine dose rate (Sv/hr). The external exposure risk is highest close to the source (up to $\sim8.6\times10^{o1}$ Sv/hr) and declines with distance and arrival time (hour:min), which shows how long it takes the plume to reach each location. It mirrors ground deposition values. The plume exhibits a rapid release under windy or neutral stability circumstances, reaching a distance of around two kilometers in less than a minute. Arrival time is more than an hour over 20 km (ICRP 60,1991; IAEA, 2010; Anvari and Safarzadeh, 2012; Malek *et al.*, 2012 and Muswema *et al.*, 2016).

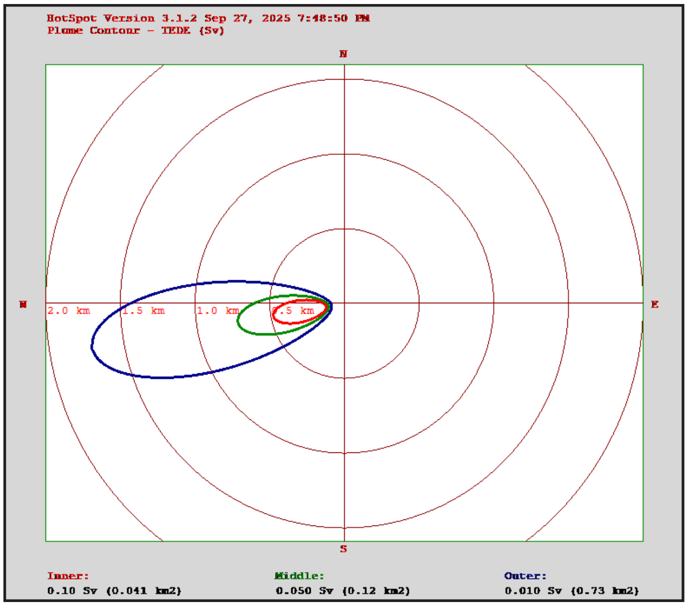

Figure (4): Plume at 30 minutes (Scenario 1)

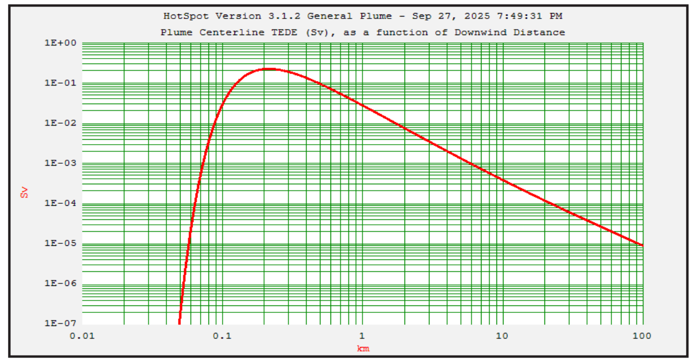

Figure (5): (Scenario 1) TEDE (in Sv) variation from the release point (height of 1,5 meters)

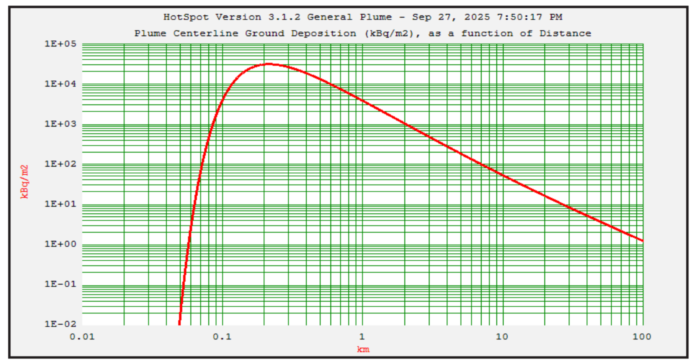

Figure (6): (Scenario 1) TEDE (in Sv) variation from the release point (ground level)

Table 3. (Scenario 1) Output value from HOT SPOT

Distance(Km)	T E D E(Sv)	Air Concentration (Bq-Sec)/M3	Ground Surface Deposition (Kbq/M2)	Ground Shine Dose Rate (Sv/Hr)	Arrival Time (Hour:Min)
0.03	0.00E+00	1.60E-09	8.20E-16	0.00E+00	<00:01
0.1	3.10E-02	1.40E+09	4.20E+03	8.60E-08	<00:01
0.2	2.30E-01	1.00E+10	3.10E+04	6.30E-07	<00:01
0.3	1.90E-01	8.70E+09	2.60E+04	5.30E-07	<00:01
0.4	1.30E-01	6.10E+09	1.80E+04	3.70E-07	<00:01
0.5	9.40E-02	4.30E+09	1.30E+04	2.60E-07	<00:01
0.6	6.90E-02	3.20E+09	9.60E+03	1.90E-07	0:01
0.7	5.30E-02	2.40E+09	7.30E+03	1.50E-07	0:01
0.8	4.20E-02	1.90E+09	5.70E+03	1.20E-07	0:01
0.9	3.40E-02	1.50E+09	4.60E+03	9.40E-08	0:01
1	2.80E-02	1.30E+09	3.80E+03	7.70E-08	0:01
2	7.40E-03	3.40E+08	1.00E+03	2.10E-08	0:03
4	2.00E-03	9.30E+07	2.80E+02	5.70E-09	0:07
6	9.60E-04	4.40E+07	1.30E+02	2.70E-09	0:11
8	5.80E-04	2.60E+07	7.90E+01	1.60E-09	0:14
10	3.90E-04	1.80E+07	5.40E+01	1.10E-09	0:18
20	1.20E-04	5.50E+06	1.60E+01	3.30E-10	0:36
40	3.80E-05	1.80E+06	5.30E+00	1.10E-10	1:13
60	2.00E-05	9.30E+05	2.80E+00	5.60E-11	1:50
80	1.30E-05	5.90E+05	1.80E+00	3.60E-11	2:27

Results of Accident (Scenario 2); the Accident Scenario 2 presents a variation in meteorological conditions (the stability class D has been uploaded in this case). It has been selected to analyze variation between two stability classes very different. In the figure 7**,** Plume at 30 minutes (Scenario 2), HotSpot software was used to create this figure, which depicts the radioactive plume's dispersion 30 minutes after emission. The radionuclide concentration (in Bq•s/m^3) varies with distance from the source, as indicated by the colorful contour lines. The hotspot, or maximum concentration area, where radiation exposure is highest, is indicated by the red area close to the source. As the plume disperses and dilutes downwind, the blue and black contours indicate decreasing concentrations. The elongated and thin plume shape indicates that, under Scenario 2, the wind speed is moderate and air stability is relatively strong, which limits vertical mixing but extends the plume farther horizontally. In contrast to unstable situations, this indicates that the expelled material moves farther downwind with less lateral dispersion (ICRP ***60***,1991). Figure (8): shows that, how the downwind distance from the discharge point affects the Total Effective Dose Equivalent (TEDE). Near the source, the TEDE rises quickly and peaks between 0.5 and 0.7 km before progressively declining. The maximum human exposure point, when inhalation and external exposure to the plume are most intense, is represented by the peak of the curve. As the plume disperses, dilution and radioactive decay cause the TEDE to drop quickly beyond 1 km. This curve, which exhibits a strong dependence on atmospheric dispersion characteristics and distance, is typical for a near-surface short-duration release (Muswema *et al*., 2016).

Figure (9): shows the rate of radioactive deposition on the ground as a function of distance from the release site. The majority of deposited activity takes place near the source, as indicated by the ground deposition curve, which peaks between 0.2 and 0.5 km. Beyond this point, the deposition gradually diminishes, indicating that tiny particles stay in the air longer and disperse farther, while larger particles settle earlier. This curve has a TEDE-like form, except it shows surface contamination instead of human dose. As a result, the area one kilometer downwind is the most contaminated, thus increasing exposure to ground shine (Bellecci *et al*., 2010 and Dahia *et al*., 2018).

Table (4): displays the simulated plume's numerical results at different distances from the release source (0.03–50 km). The TEDE, air concentration, ground surface deposition, ground shine dosage rate, and plume front arrival time are all included. TEDE (Sv) stands for total effective dose equivalent, which combines exterior exposure and inhalation. Near 0.6 km, the TEDE reaches its maximum (~0.22 Sv), after which it diminishes as the plume spreads. Near the peak exposure position, the air concentration (Bq•s/m^3) is at its highest (~1.7×10^1 Bq•s/m^3); it drastically decreases after one kilometer. reflects the air's radionuclide density. Deposition on the ground surface (kBq/m2), Peaks at 0.6 km (3.8×10^2 kBq/m2), in keeping with Figure 9's plume centerline and deposition pattern. shows the highest level of surface pollution close to the plume axis. The ground shine dosage rate (Sv/hr) exhibits a similar pattern to deposition, peaking near the source and sharply declining beyond one kilometer. represents the exposure to gamma rays from deposited material. Arrival timing (hour:min) shows the arrival of the plume at each distance. The plume disperses quickly, reaching the first kilometer in less than a minute. The arrival time increases to several minutes or hours beyond 20 km, indicating slower plume transport (Cenciarelli *et al*., 2013a and Cenciarelli *et al*., 2013b). Scenario 2 is described in Figs. (7- 9) and Table 4, which illustrate the regional variations in radionuclide concentration, dosage, and deposition following a near-surface release. Within the first kilometer (particularly between 0.5 and 0.7 km) from the source, both the maximum TEDE and deposition take place. Rapid dilution lowers exposure and contamination outside of this area. According to the findings, inhalation continues to be the primary exposure route in this situation, with ground shine making a smaller contribution at longer distances. These results emphasize how important it is to take precautions and act quickly in the immediate downwind area following a nuclear leak (Pazienza *et al*., 2013 and Pazienza *et al*., 2014).

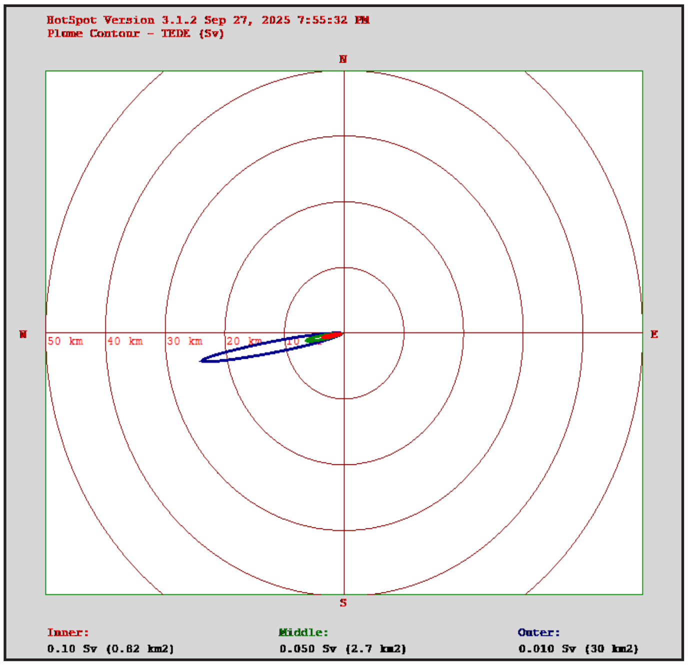

Figure (7): Plume at 30 minutes (Scenario 2)

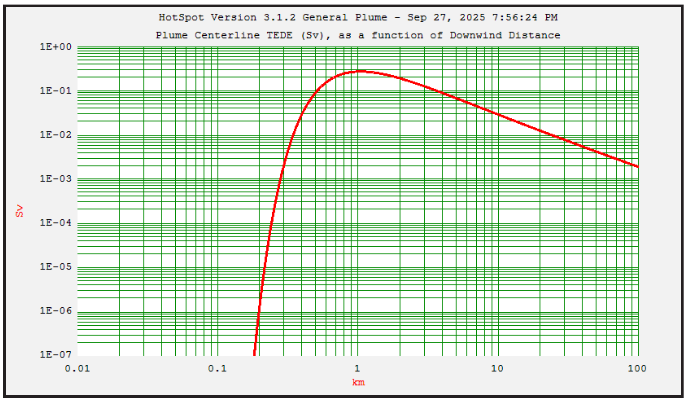

Figure (8): (Scenario 2) TEDE (in Sv) variation from the release point (height of 1,5 meters)

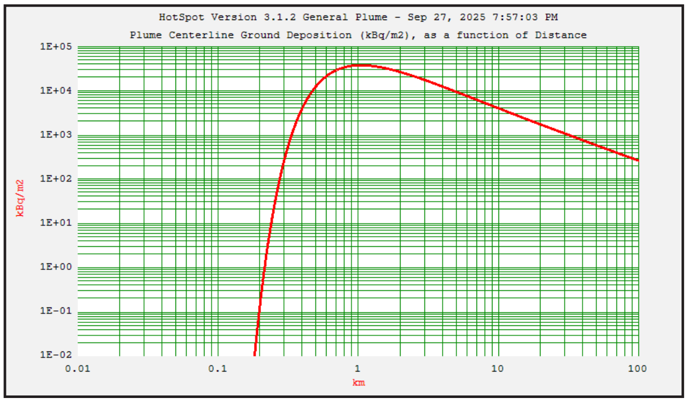

Figure (9): (Scenario 2) TEDE (in Sv) variation from the release point (ground level)

Table 4. (Scenario 2) Output value from HotSpot

Distance(Km)	T E D E(Sv)	Air Concentration (Bq-Sec)/M3	Ground Surface Deposition (Kbq/M2)	Ground Shine Dose Rate (Sv/Hr)	Arrival Time (Hour:Min)
0.03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	<00:01
0.1	0.00E+00	2.60E-12	0.00E+00	0.00E+00	<00:01
0.2	2.00E-06	9.00E+04	2.00E-01	4.10E-12	<00:01
0.3	2.70E-03	1.20E+08	3.50E+02	7.00E-09	0:01
0.4	3.30E-02	1.50E+09	4.40E+03	8.80E-08	0:01
0.5	9.70E-02	4.50E+09	1.30E+04	2.70E-07	0:02
0.6	1.70E-01	7.60E+09	2.30E+04	4.60E-07	0:02
0.7	2.20E-01	1.00E+10	3.00E+04	6.10E-07	0:02
0.8	2.50E-01	1.20E+10	3.50E+04	7.00E-07	0:03
0.9	2.70E-01	1.20E+10	3.70E+04	7.50E-07	0:03
1	2.80E-01	1.30E+10	3.80E+04	7.70E-07	0:04
2	1.90E-01	8.80E+09	2.70E+04	5.40E-07	0:08
4	9.00E-02	4.10E+09	1.20E+04	2.50E-07	0:16
6	5.50E-02	2.50E+09	7.50E+03	1.50E-07	0:25
8	3.80E-02	1.80E+09	5.30E+03	1.10E-07	0:33
10	2.90E-02	1.30E+09	4.00E+03	8.10E-08	0:42
20	1.20E-02	5.70E+08	1.70E+03	3.50E-08	1:24
40	5.50E-03	2.50E+08	7.60E+02	1.50E-08	2:49
60	3.40E-03	1.60E+08	4.70E+02	9.60E-09	4:14
80	2.50E-03	1.10E+08	3.40E+02	6.90E-09	5:39

Conclusions

The study's results explain that modeling radioactive material dispersion with HotSpot software is a useful tool for helping in nuclear emergency decision-making. The simulation showed a strong ability to describe the radioactive cloud's behavior and precisely locate hazard zones with the necessary temporal and spatial accuracy, and its demonstrated that the first kilometer from the emission site is where the highest levels of radiation exposure and ground deposition are concentrated, with wind speed and air stability having a significant impact, this confirm how important climatic factors are in influencing the level and dispersion of radioactive contamination. Additionally, the analysis of the dispersion pattern and intensity of radioactive accumulation varies significantly depending on the atmospheric stability classes, this shows the importance of meteorological data incorporate for emergency response strategies. and from this work the two scenarios are compared, it is evident that Scenario 1's plume area is wider than Scenario 2's, and the plume is spread across a larger surface and according to the simulation results, the highest value of contamination is 3.10E+04 (kBq/m2) at a distance of 210 meters from the release point for Scenario 1 and 3.80E+04 (kBq/m2) at a distance of 1 km for Scenario 2, and its notice for Scenarios 1 and 2, the plume maps display the geographical dispersion of radioactive elements after 30 minutes ,the hot spot, or greatest concentration, forms an elongated shape along the wind direction and emerges near the release site before progressively decreasing with distance, the plume in Scenario 2 is longer and thinner, suggesting more stable atmospheric conditions that promote horizontal transport while limiting vertical mixing, due to dilution and decay , the Total Effective Dose Equivalent (TEDE) rises quickly close to the source, peaking between 0.5 and 0.7 km before declining with distance, this peak zone represents the maximum area where humans could be exposed to radiation by inhalation and external exposure, the majority of radionuclides land on the surface near the source (around 0.5–1 km), where the ground deposition rate (kBq/m2) likewise peaks. As lighter particles stay in the air longer beyond this range, deposition drastically decreases, indicating that surface contamination is mostly contained close to the release location, displays arrival time, TEDE, air concentration, and ground deposition at various distances, Near 0.6–0.7 km from the release point, the greatest TEDE (≈0.19 Sv) and ground deposition (≈1.3×10^2 kBq/m^2) take place, the plume confirms early-stage rapid dispersion by reaching the first kilometer in less than a minute, shows a similar pattern, but the concentration and dosage values are somewhat greater, suggesting that Scenario 2 conditions—a more stable atmosphere—cause a stronger local accumulation of radioactive particles and Once more, the highest TEDE (≈0.22 Sv) and ground deposition (≈3.8×10^2 kBq/m^2) occur close to 0.6 km before decreasing with distance. Thus, the work explains that employing advanced computer models as a prediction tool can greatly enhance prevention strategies and lessen the hazards to human health and the environment risk by nuclear accidents.

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