

Analysis of a Radiological Incident in Nuclear Power Plant and Simulation of the Radioactive Material Dispersion

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Abstract— The report examines the behaviour of a radionuclide released during an accident at a nuclear power plant. The analysis focuses exclusively on caesium to provide specific and detailed information about its characteristics and dispersion. Experiments were conducted under different atmospheric stability conditions to track changes in the plume's behaviour.

The hypothetical model used in this analysis can be easily applied to assess radiation scenarios in similar events. This approach is instrumental in assisting first responders and guiding defensive actions. It also aids in establishing general operational guidelines and evaluating population exposure risks.

Keywords— radiological event, hazard, modelling and simulation, atmospheric dispersion, radionuclide, cesium-137, NPP accidents.

I. INTRODUCTION

The security of nations is increasingly threatened by asymmetric threats, including those posed by national and international terrorism. According to international humanitarian law (IHL), the deliberate use of radiological hazards as weapons could be considered a violation of the principles of distinction and proportionality, key elements in the protection of civilian populations during armed conflict. Radiological weapons or incidents that cause indiscriminate harm may also violate the prohibition against causing unnecessary suffering, as outlined in the Geneva Conventions and their Additional Protocols. Such weapons can exploit vulnerabilities in populations, creating psychological distress, inflicting life-threatening harm, and causing long-term environmental damage, all of which are contrary to the fundamental protections afforded under IHL. Furthermore, certain radioactive particles, such as alpha emitters, pose detection challenges, requiring

specialized personnel and equipment for mitigation, which may not be readily available, further complicating humanitarian responses and recovery efforts in accordance with IHL obligations. [1]-[4]

Depending on the characteristics of radiological agents, they can affect personnel, equipment, and infrastructure through neutron or gamma irradiation, as well as contamination by alpha or beta particles. Radiation exposure occurs through direct irradiation, external contamination (contact with skin and clothing), or internal contamination (inhalation or ingestion). [5]

Radiological leakage encompasses accidental releases, indirect damage, or deliberate sabotage targeting nuclear, industrial, or medical facilities that handle radioactive materials. [6]-[8] These facilities include, but are not limited to, nuclear power plants, research reactors, nuclear fuel processing and enrichment plants, radioactive waste storage facilities, and medical or industrial sites that utilize radioactive sources.

Additionally, radiological hazards can arise from transportation accidents involving radioactive materials transported via road, rail, or water. Ensuring protection against NPP accidents is a matter of national security, as such incidents have direct consequences for both human safety and environmental integrity. The primary objective of this research is to demonstrate the use of software tools for simulating radiological dispersion following an NPP accident. The simulation assists in determining potential evacuation routes, identifying affected areas, and predicting radioactive fallout. Given the prevalence of radioactive elements in nuclear energy production, it is crucial to develop decision-support systems that minimize risks to the population and environment.

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Radiation accidents typically involve significant emissions within the first 10–12 days. Most major fission products, including isotopes of tellurium (Te), iodine (I), barium (Ba), lanthanum (La), cerium (Ce), ruthenium (Ru), strontium (Sr), yttrium (Y), zirconium (Zr), niobium (Nb), silver (Ag), and cesium (Cs), can be detected in atmospheric aerosols from the radioactive cloud. Fortunately, alpha-emitting nuclides tend to remain near the accident site in limited quantities. [9]

II. MATERIALS AND METHODS

Protection against radiation exposure requires strict adherence to absorbed dose limits for workers and the general population. Annual total body equivalent dose limits are set at 1 mSv for the public and 50 mSv for occupational workers.

To simulate the dispersion of ^{137}Cs , a specialized software tool was employed to model various atmospheric conditions. Radioactive materials released during NPP accidents disperse in the form of gases and particles, with their concentration in air and deposition on soil dependent on several factors, including:

- 1) Amount of radionuclide released.
- 2) Height of the emission source.
- 3) Wind speed and atmospheric stability.

Physical and chemical properties of the released material.

The Hotspot software suite was used to simulate emergency response scenarios, assess facility safety, and estimate the dispersion of radioactive plumes. Hotspot's atmospheric dispersion model provides a first-order approximation of radiological effects associated with short-term (less than 24 hours) releases, primarily applicable to near-surface emissions in open terrain under various weather conditions.

The simulation incorporated two scenarios: 1) A release of ^{137}Cs accompanied by fire and 2) A release of ^{137}Cs accompanied by an explosion.

Cesium-137 was chosen due to its significant role in radiation exposure following nuclear incidents, such as the Chernobyl disaster. The primary objective was to evaluate its dissipation within the first hour of the incident. [10]

Hotspot utilizes the Gaussian plume model, which has been extensively validated for initial dispersion estimates and worst-case safety analyses. The software integrates radiation dosimetry methodologies recommended by the International Commission on Radiological Protection (ICRP) and Environmental Protection Agency (EPA) guidelines.

The mathematical model used to estimate airborne radioactive concentration (C) at a given location is expressed as follows [11]:

$$C(x, y, z, H) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{ \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] \right\} \exp\left[-\frac{\lambda x}{u}\right] \cdot DF(x) \quad (1)$$

Where:

C - time-integrated atmospheric concentration (Ci-s/m³);

Q - source term (Ci);

H - effective release height (m);

X - radioactive decay constant (s⁻¹);

u - wind speed at release height (m/s);

σ_y, σ_z - standard deviations in lateral and vertical plume spread (m);

DF(x) - depletion factor accounting for deposition losses.

Since the release can be of longer or shorter duration, this parameter can be modified by introducing a dispersion correction factor σ_y' [11-13]:

$$\sigma_y' = \sigma_y \left(\frac{t}{10}\right)^2 \quad (2)$$

The following values were selected for baseline data: material at risk (MAR) $1,5 \cdot 10^{16}$ Bq, damage ratio (DR) 1,00, leakage factor 1,00, air fraction (ARF) 1,00, a respirable fraction (RF) of 1,00 and a deposition rate of 0,15 cm/s. Specifically, in the case of the accompanying fire, the cloud height is set to 10 m. For the general explosion scenario, all parameters were unchanged, adding an explosive with 90,9 kg (200 lb) of TNT. [14]

The maximum deposition rate can reach up to $6 \cdot 10^{-2}$ m.s⁻¹ in some cases. However, the rate of deposition depends on atmospheric stability. Under moderately stable atmospheric conditions (usually at night, clear skies), Jensen [15] proved that u is only half of its value under neutral conditions. Thus, the maximum deposition rate should then, according to equation (3), be only a quarter of the value, i.e. $< 1,5 \cdot 10^{-2}$ m.s⁻¹.

$$v_i = \frac{u_*^2}{u} \quad (3)$$

The deposition rate includes two components: v_i eddy diffusion and v_s sedimentation. This is an important expression that puts an upper bound on the eddy-diffusion component of the total deposition rate. u_* is proportional to the frictional tangential rotation speed of the particles in the flow.

Boundary conditions were selected in terms of total equivalent dose equivalent TEDE and land deposition (soil radioactivity value in kBq/m²). For TEDE, the intrinsic, mean, and extrinsic parameters were defined as 5 Sv

(25 rem) (threshold for immediate deterministic effects), 20 mSv (0,2 rem) (maximum dose for first responders), and 1 mSv (0,1 rem) (evacuation operational level). Values of 3700 kBq/m² (100 μCi/m²), 370 kBq/m² (10 μCi/m²) and 37 kBq/m² (1 μCi/m²) were selected for the internal, medium and external terrestrial deposition parameters. The total effective dose equivalent (TEDE), which includes external and internal contributions to the total absorbed dose and deposition of the contaminant on the ground, has been calculated for different categories of atmospheric stability, several particle size distributions of the contaminant, different amount of explosive.

The meteorological conditions under which the research was done are wind speed at a height on 10 m is 10 m/s, for the stability of the atmosphere very stable vertical resistance A and neutral D on the Pasquill–Gifford scale was used.

Simulation models offer risk-free testing, cost savings, and efficiency improvements across various fields. They enhance decision-making by analysing different scenarios, support hands-on training, and accelerate innovation. Their predictive power helps forecast trends, optimize operations, and improve scalability. Overall, simulations provide a flexible and effective way to experiment, learn, and plan. [16]-[20]

III. RESULT AND DISCUSSION

The HotSpot software allows the user to visualize both TEDE contour plots and radioactive deposition contour plots, which show the relative values as a function of distance along the plume line. Radioactive deposition contour plots for the scenario are shown in Fig. 1 (a, b).

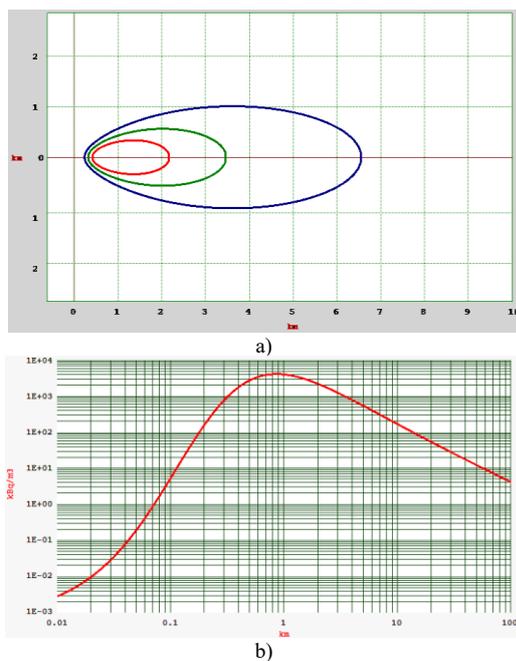


Fig. 1. Dependence of terrestrial radioactive deposition on the center of the accident accompanied by fire in vertical

stability class A: a) areas of radioactive deposition b) graphical dependence on concentration and distance

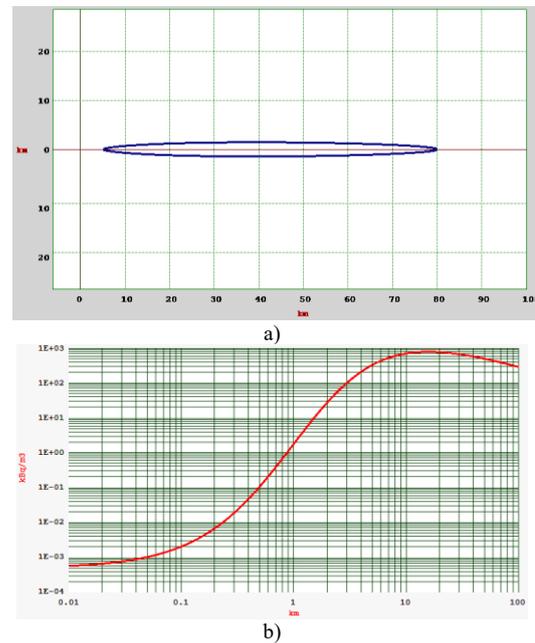


Fig. 2. Dependence of terrestrial radioactive deposition on the center of the accident accompanied by fire in vertical stability class A: a) areas of radioactive deposition b) graphical dependence on concentration and distance

Figures 1 and 2 depict the results of the simulation of a radiation accident and the dispersal of ¹³⁷Cs. In the input data presented above, for vertical resistance class A, the zones have clearly defined boundaries, with personnel at approximately 2 km from the accident site potentially absorbing up to 5 Sv. The red zone covers an area of 0,92 km². The zone where no values exceeding 1 mSv (0,1 rem) are observed is considered the operational evacuation threshold and is 10,7 times larger than the red zone.

The measured Total Effective Dose Equivalent (TEDE) values indicate that the selected conditions do not pose a deterministic risk, as the corresponding threshold (5 Sv) is not reached. For vertical resistance class D, a terrestrial radiation deposition zone of up to 37 kBq/m² (1 μCi/m²) extends up to 80 km from the accident site.

In the simulation of a radiation accident with an accompanying explosion under the specified conditions, the probability of fatality reaches up to 99 % for individuals located within 10 m of the accident site. The TEDE values again indicate that the selected conditions do not lead to a deterministic risk, as the 5 Sv threshold is not exceeded. However, the simulation revealed areas with TEDE values exceeding 20 mSv, extending up to 0,5 km for vertical resistance A and 1 km for vertical resistance D, necessitating the immediate evacuation of the area.

Furthermore, considering the outer affected area, which ranges from 9,5 km² to 286 km², it can be inferred that at a maximum distance of approximately 95 km from the accident site, under vertical resistance class D, radiative deposition at the Earth's surface would reach at least 1 mSv.

Contour plots for terrestrial deposition illustrate the maximum distances with depositional boundaries from the centre of dispersal (hot spot). Comparing the areas obtained for resistance class A, the outer zone extends 9,8 km² in the case of fire and 9,5 km² in the case of an explosion, showing insignificant differences. However, the blue zone areas measure 168 km² and 286 km², respectively, demonstrating that the resistance class significantly impacts the spread of ¹³⁷Cs following a nuclear power plant accident involving an explosion, unlike scenarios with fire alone.

This experimental evidence further confirms that the Hotspot software platform can reliably simulate the release of ¹³⁷Cs in a nuclear power plant accident of this magnitude.

IV. CONCLUSIONS

Hotspot allows users to create a custom “mixture of radionuclides.” However, for the purposes of this development, we have chosen to estimate the release of a single radionuclide to better understand its contribution to the Total Effective Dose Equivalent (TEDE). The software enables the visualization of both ground deposition and TEDE contours at the release site in Google Earth by incorporating the geographic coordinates of the reactor where the incident occurred.

Managing the risk of a radiological event is crucial, as it cannot be eliminated, regardless of how robust the nuclear power plant (NPP) protection system is. Atmospheric dispersion modelling software plays a vital role in mitigating the impact of radiological dispersion during such events. Due to the limited availability of specific contamination data following NPP accidents, certain parameter approximations were necessary to construct comparative scenarios. However, the deposition scenario can be replicated with comparable magnitudes under different initial conditions, such as variations in elevation and wind speed.

For this scenario, the General Explosion and General Fire models within the Hotspot code have proven to be effective in estimating the ground deposition of ¹³⁷Cs.

The author contributed to the adaptation and customization of the Hotspot modelling environment for the purposes of scenario analysis, specifically focusing on the release and deposition patterns of cesium-137. The comparative modelling methodology developed by the author allows for quick scenario reconstruction with limited data, making it applicable in both civil protection planning and training of emergency response teams.

The obtained results can be used for:

- Preparing emergency response strategies for potential radiological incidents.
- Developing training simulations for CBRN (Chemical, Biological, Radiological, Nuclear) protection units.
- Supporting national risk assessments and crisis management protocols involving NPPs.
- Enhancing public safety by contributing to evacuation planning and contamination zone prediction.

These contributions not only support scientific understanding of atmospheric radionuclide dispersion but also provide a practical toolset for decision-makers and first responders.

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