ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/380637154

# Radiological consequence assessment of a hypothetical accident at the Rooppur nuclear power plant using Hotspot simulation software

**Conference Paper** · March 2024

DOI: 10.5281/zenodo.11204883

CITATION
1

READS
92

3 authors:

Abu Bakker Chiddiq
Khulna University of Engineering and Technology
**3** PUBLICATIONS **5** CITATIONS

SEE PROFILE

Md. Asif All Azad
The Ohio State University
**10** PUBLICATIONS **7** CITATIONS

SEE PROFILE

Md Rubel Miah
Bangladesh University of Engineering and Technology
**4** PUBLICATIONS **6** CITATIONS

SEE PROFILE

All content following this page was uploaded by Md. Asif All Azad on 17 May 2024.

The user has requested enhancement of the downloaded file.

# RADIOLOGICAL CONSEQUENCE ASSESSMENT OF A HYPOTHETICAL ACCIDENT AT THE ROOPPUR NUCLEAR POWER PLANT USING HOTSPOT SIMULATION SOFTWARE

**Abu Bakker Chiddiq*[1], Md. Asif All Azad[2] and Md. Rubel Miah[3]**

[1] *Undergraduate student, Khulna University of Engineering & Technology, Bangladesh, e-mail: chiddiq.24.che@gmail.com*
[2] *Undergraduate student, Khulna University of Engineering & Technology, Bangladesh, e-mail: asif.che.kuet@gmail.com*
[3] *Undergraduate student, Khulna University of Engineering & Technology, Bangladesh, e-mail: rubelmiah2000@outlook.com*

***Corresponding Author**

## ABSTRACT

A hypothetical major accident at Bangladesh's planned Rooppur Nuclear Power Plant has been evaluated by this study. The health physics code employed for this evaluation is HotSpot 3.1, developed by Lawrence Livermore National Laboratory in the United States. The source term for this technique has been determined analytically. A number of factors are considered during the assessment, including the meteorological conditions, release characteristics, and protective measures implemented by the Bangladesh Meteorological Department. This assessment evaluates potential radiological consequences of a severe accident situation. In the study, different accident scenarios are examined, including situations where core damage leads to the release of radioactive materials. The TED (total exposure duration) and GD (ground deposition) values have been computed for six distinct scenarios at various points along the plume centerline, extending up to 100 km from the release location. The examination of demographic data indicates that scenario A exhibits the highest prevalence of affected individuals since it is more widely distributed. Through its analysis of global risk reduction opportunities and challenges, this study contributes to the discussion on nuclear safety and emergency preparedness.

***Keywords:*** *Rooppur nuclear power plant, hypothetical accident, radiological repercussions*

## 1. INTRODUCTION

Many nuclear research reactors around the world have been operating for periods facing levels of performance and occasional challenges. When designing reactors, experts analyze potential accident scenarios that could lead to core damage and the release of significant amounts of radioactive materials into the environment. Reactor accidents such as reactivity changes, blockage of primary coolant flow or loss of coolant are examples that can potentially cause damage to the reactor core (Obeng et al., 2021). During operation nuclear reactors maintain performance and do not release significant amounts of radioactive substances into the surrounding environment. However, if an accident occurs that goes beyond the expected design limits and leads to core melting it could result in an event where a substantial amount of inventory is released into the atmosphere. This poses risks to the safety and wellbeing of both plant personnel and the general population. The level of threat depends on the quantity of radionuclides released and the magnitude of the accident causing their discharge. It is crucial to examine radiological hazards following such a hypothetical catastrophic event considering the severe and potentially life-threatening dangers posed by nuclear radiation. Therefore, it is vital to subject nuclear power plant designs to testing in order to evaluate their ability to mitigate these risks effectively. Hence it is crucial to examine the consequences of a nuclear reactor mishap and establish a contingency plan, for handling radiological emergencies and severe accidents before the reactor goes into commercial operation (Fairuz & Sahadath, 2020). Unintentional releases of material from reactors can lead to exposure to radiation doses externally within the human body. In the field of radiation protection and dosimetry we use the term " dose equivalent (TEDE)" to quantitatively evaluate an individual’s overall radiation exposure. This evaluation considers the sum of doses from different sources of radiation each with their own unique biological effects. Therefore, the equivalent dose is used to estimate the amount of radiation exposure considering the varying effects of types of radiation. Another used term when discussing radioactivity is ground deposition. Ground deposition refers to the process by which particles, chemicals or contaminants settle on the Earth’s surface from the atmosphere. This encompasses substances such, as dust, ash or chemical pollutants. There are ways through which these substances can settle on the ground including gravity pulling them down precipitation or particles adhering to surfaces. Factors like particle size, atmospheric conditions, wind patterns and particle characteristics all contribute to this phenomenon. The release of elements from the ventilation systems of reactors led to their scattering from the chimneys. These radioactive elements which can be in particulate form have the ability to escape into the atmosphere and be carried by wind currents to areas. The concentration of radionuclides in both the air and on the ground depends on factors, such as the number of radionuclides released, wind speed, atmospheric stability and other variables studied in this research investigation. It is possible that a situation could have occurred where there was a malfunction in the ventilation system specifically affecting the operation of ventilation supply fans, for rooms. (Anvari & Safarzadeh, 2012). Moreover, it's possible that some radioactive material might have been released from the reactor stack affecting the area. To minimize the risks associated with the release of substances it is important to assess both the total effective dose equivalent (TEDE) and the genetic dose (GD) resulting from the dispersion of these materials. This evaluation plays a role, in ensuring radiation safety and preserving the health of the surrounding community. The Rooppur Nuclear Power Plant (RNPP) is currently being constructed in Ishwardi, Pabna, Bangladesh. It is located at coordinates 24°4′0″ N, 89°2′ 50″ E. The plan is for the two units of the power plant to start operating in 2024. This power plant belongs to Generation III+ reactors. Has been specifically designed based on the VVER 1200 AES 2006 model. Despite the safety features of Generation III+ reactors that make them more durable there is still a chance of core damage occurring with a frequency of approximately 10 (Fairuz & Sahadath, 2020). Although the chances are low there is a possibility of an incident taking place. This study focuses on examining the consequences that could arise from such a catastrophe, at the RNPP using the air dispersion modelling software called HotSpot. The HotSpot Health Physics code, created by the National Atmospheric Release Advisory Centre (NARAC) at Lawrence Livermore National Laboratory aims to provide emergency response personnel and planners with a set of software tools that can be quickly deployed to evaluate incidents involving materials. This program is also used to assess safety measures, in facilities that handle substances. The atmospheric dispersion

models used by the HotSpot software offer an estimate of the radiation impacts resulting from releases of radioactive materials into the air particularly for durations shorter than a few hours.
In addition, these methods are specifically designed to handle short term emissions that last 24 hours in areas with terrain and weather conditions. The HotSpot software uses a model to forecast how material spreads. This model has been thoroughly validated over the years making it reliable, for estimating dispersion or conducting safety investigations in worst case situations. The methods used in this study are based on a known model (GPM) which is frequently employed to assess emergencies or plan safety analyses related to releases. One notable advantage of GPM is its fast computation speed, which allows for data processing. It is also possible to simulate the spread of matter related to events such, as fires, explosive releases, resuspension or user defined geometries using virtual source terms (Rennie, n.d.).

## 2. METHODOLOGY

The dispersion of radionuclides resulting from a hypothetical accident at the Rooppur Nuclear Station was simulated using general explosion scenarios by HotSpot Software.

### 2.1 Simulation of Unexpected Scenario

The initial and primary factors leading to the nuclear reactor catastrophe was the exposure of radioactive fuel and the subsequent collapse of the core structure. A Loss of Coolant Accident (LOCA) is the primary mechanism via which the primary coolant of the reactor core is depleted, leading to a situation where the fuel is insufficiently cooled. This research encompasses a forecasted scenario that involves a significant major break-loss-of-coolant accident (LBOCA) and a station blackout occurring within one of the reactor units of the RNPP. It is postulated that the emergency core cooling system may be rendered inoperable in the event of an unforeseen and undesired scenario, hence impeding the initiation of the refilling procedure. The convergence of these forces results in a rapid decrease in core pressure, ultimately leading to the formation of steam. Consequently, the core initiates the process of melting. During the process of a nuclear reactor shutdown, by-products of fission, as well as highly reactive substances, are released into the confinement environment. Moreover, the deficiency of off-site power is the underlying cause of the malfunctioning of filtration and ventilation systems. The exit of radioactive materials from the containment area through the vent stack is attributed to the inadequate sealing of an isolation valve within the ventilation system. As a result, the release elevation is aligned with the height of the vent stack, which has been established at 100 metres based on observations from the Kudankulam reference plant utilising VVER technology (Jafarikia & Feghhi, 2018). The absence of established protocols to restrict the occurrence of this hypothetical unintended incident results in the reduction factor (RDF) and the escape fraction (EF) being assigned a value of 1. This hypothetical accident scenario can be classified as an INES level 7 event based on the magnitude of the released activity. The functionality of the core catcher, a method employed for ex-vessel melt retention (EVMR) in VVER 1200 reactors, was compromised due to the accident scenario, including an in-vessel core meltdown.

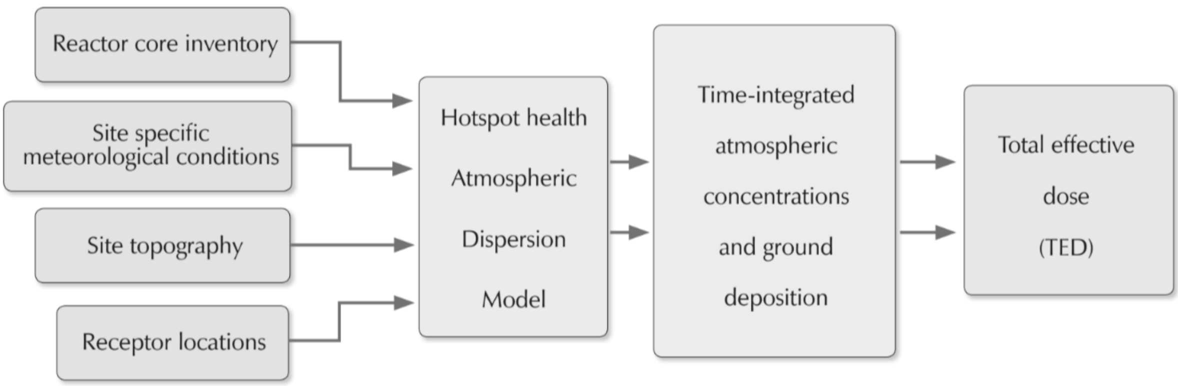


Figure 1: General methodology calculation by HotSpot (Dahia et al., 2022)

## 2.2 Estimating the Source Term

The word "source term" in the context of radioactivity pertains to the dimensions and composition of radioactive substances that are discharged from the fuel. The aforementioned quantities are referred to as fractions of the inventory of fission products in the fuel. A comprehensive selection of 49 radioactive elements was made based on existing literature, with particular emphasis on VVER 1000 reactors (Jafarikia & Feghhi, 2018). The elements mentioned can be classified into eight distinct groups: Noble gases, Halogens, Alkali metals, Tellurium group, Ba/Sr group, Noble metals, Cerium group, and Lanthanides. The HotSpot study employed FGR 13 from the Dose Conversion Factor (DCF) collection.

The ultimate source term has been computed employing the subsequent straightforward equation:

$$ST = \left[\left\{\frac{Activity\ (Ci)}{MW_{th}}\right\} \times (3200MW_{th}) \times RF \times RDF \times EF\right] \quad (1)$$

where,
Core Thermal power =3200$MW_{th}$
EF= Escape fraction
RDF = Reduction factor
RF= Release fraction

The release fractions (RF), which indicate the proportion of radionuclides released, were derived from NUREG-1465, specifically for the case being examined in this research. Burnup has an impact on the quantity of long-lived radionuclides present in the core inventory. The burnup of VVER 1200 reactors is reported to be 60 gigawatt days per metric tonne of heavy metal (GWD/tHM), but the initial activity per megawatt is documented as 38.585 GWD/tHM. Consequently, the estimation of the inventory for long-lived nuclides has been conducted utilising an approach based on equations, as depicted in Table 1.

$$I_{Actual} = I_{38,585} \times \frac{60{,}000(MWD/tHM)}{38{,}585(MWD/tHM)} \quad (2)$$

where, tHM= tons of heavy metal

The contribution of radionuclides to the source term is influenced by various factors, including the number of fission products, the physical state of the nuclide, its chemical reactivity, its response to reduction processes, and the severity of the accident. Figure 2 illustrates the observed levels of activity for the eight groups.

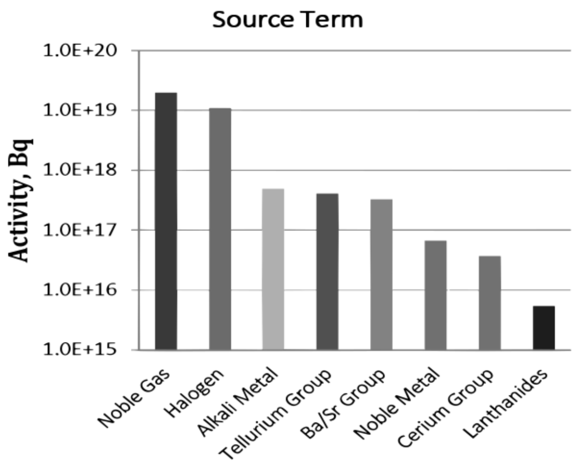


Figure 2: Activity levels of different groupings of radionuclides (Fairuz & Sahadath, 2020)

Table 1 that Noble gas and Halogen exhibits significantly higher activity levels compares to other groups. This quantitative assessment is instrumental in evaluating the radiological consequences and implementing effective mitigation strategies.

Table 1: Source terms used for the hypothetical accident in this study

| **Group** | **Radionuclides** |
|---|---|
| Noble gas | Kr-83m, *Kr-85, Kr-85m, Kr-87, Kr-88, Xe-131m, Xe-133, Xe-133m, Xe-135, Xe-135m |
| Halogen | I-131, I-132, I-133, I-134, I-135 |
| Alkali metal | *Cs-134, Cs-136, *Cs 137, Rb-86 |
| Tellurium | Te-127, Te-127m, Te-129, Te-129m, Te-131m, Te-132, Sb-127, Sb-129 |
| Ba/Sr group | Ba- 140, Sr-89, *Sr-90, Sr-91, Sr-92, Mo-99 |
| Noble Metal | Ru-103, Ru-105, Rh-105, *Ru-106, Tc-99m |
| Cerium | Ce-141, Np-239, *Pu-241 |
| Lanthanides | Cm-242, La-140, Nd-147, Pr-143, Y-90, Zr-95, Zr-97 |

*long lived radionuclide (Half-life >1 year)

## 3. RESULTS AND DISCUSSION

Table 2 displays the tabular data about the outputs of hotspots in General explosion scenarios. The graphical representations of the outcomes obtained from the simulated scenarios are illustrated in Figures 4 and 5. The provided figures depict the concentration of ground deposition and the dose of total effective dose equivalent (TEDE), respectively. The data is presented using the Cartesian coordinate system, where the x-axis is aligned with the primary wind direction. Understanding the potential impact on the environment and human health of general explosion scenarios depends on the boundary conditions. The source term characteristics are defined by a radionuclide mix, which is considered to be homogenous with a damage ratio, leak path factor, airborne fraction (ARF), and respirable fraction (RF) all assigned a value of 1.0, indicating a worst-case scenario where the entire inventory is available for dispersion. The explosive parameters are modeled using a high explosive weight of 150,000 pounds, with a 10-meter per second wind speed blowing towards the west (270 degrees). The stability class for the scenario is categorized as 'A', representing very unstable atmospheric conditions which are conducive to greater dispersion. Meteorological conditions are further characterized by a non-respirable deposition velocity of 8 centimeters per second and a receptor height of 1.5 meters, which corresponds to the average height of a human's breathing zone. The sample time for measuring these conditions is set at 10 minutes, with a reference wind height of 10 meters, and a breathing rate of $4.17\times10^{-4}$ cubic meters per second, providing a realistic framework for potential human exposure. The total effective dose equivalent (TEDE), which is a measure of the radiation dose to a person, is stratified into three contour doses: an inner contour dose of 1.0 sievert, which indicates a high level of immediate concern; a middle contour dose of 0.5 sieverts; and an outer contour dose of 0.05 sieverts, which represents the periphery of the impact zone. The deposition of radionuclides is represented using kilobecquerels per square meter, which decrease from the center outward, specified as 100,000 kBq per square meter for the inner zone, 10,000 kBq per square meter for the middle zone, and 1,000 kBq per square meter for the outer zone. These values provide a quantitative basis for evaluating the severity and reach of contamination following a general explosion event involving radionuclides.

Table 2: Boundary conditions for the general explosion scenarios

| | Parameter | Value |
|---|---|---|
| Source term characteristics | Source material | Radionuclide Mix |
| | Damage ratio | 1.0 |
| | Leakpath factor | 1.0 |
| | Airborne fraction (ARF) | 1.0 |
| | Respirable fraction (RF) | 1.0 |

**General Explosion scenario**

| | | |
|---|---|---|
| Explosive | High explosive (lb) | $1.5\times10^5$ |
| Meteorological conditions | 10 m wind speed (m/s) | 10 |
| | Wind direction | 270 west |
| | Stability class | A |
| | Atmospheric stability (actual stability) | Very unstable |
| | Non-respirable deposition velocity (cm/s) | 8 |
| | Receptor height (m) | 1.5 |
| | Sample time (min) | 10 |
| | Wind ref. Height (m) | 10 |
| | Breathing rate ($m^3$/s | $4.17\times10^{-4}$ |
| TEDE (Sievert) | Inner contour dose | 1.0 |
| | Middle contour dose | 0.5 |
| | Outer contour dose | 0.05 |
| Deposition (kBq/m²) | Inner | 100000 |
| | Middle | 10000 |
| | Outer | 1000 |

Figure 3 exhibits the contour plot representing the TEDE plume, showcasing the farthest distances of the isodose curves from the reference point (hotspot) in the direction of the prevailing wind. The region exhibiting the highest dose values is located within a range of 0.9 kilometres from the origin, where the internal dose approaches 1 Sievert (sv). A dosage value of 0.5 sv, falling between the range of 0.9 to 7 km, is considered moderate. The last curve illustrates the range of distances spanning from 7 to 35 km, whereby the cumulative effective dose equivalent (TEDE) value amounts to 0.1 sieverts (Sv). The curves encompass a total area of 0.44 square kilometres, 13 square kilometres, and 185 square kilometres, respectively.

Figure 4 displays the contour plot of ground deposition, illustrating the maximum distances of deposition curves from the zero point (hotspot) in the downwind direction. The region denoted as area I exhibits the highest values, ranging from zero point to 0.9 km, with an inner deposition value of 1.00E+00 q/$m^2$. This is followed by area II, which spans from 0.9 to 4 km and displays an intermediate deposition value of 1.1E-01 Bq/$m^2$. Lastly, AREA III, covering the distance from 4 to 21 km, demonstrates a deposition value of 1.00E-02 Bq/$m^2$. The curves collectively cover an area of 0.21 $km^2$, 4.6 $km^2$, and 79 $km^2$, respectively. Figure 4 illustrates the correlation between ground deposition and the distance downwind from the point of explosion. The plume Centerline TED (Sv) and Ground Deposition (kBq/$m^2$) for all stability classes (A-E) are shown through Figure 5.

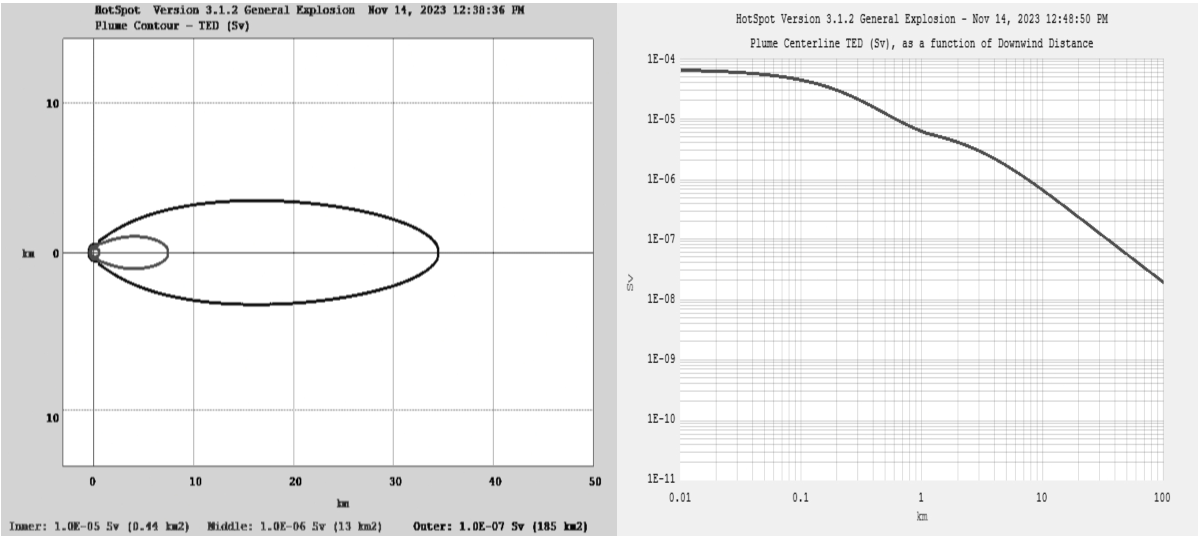


Figure 3: TEDE isodose in relation to distance

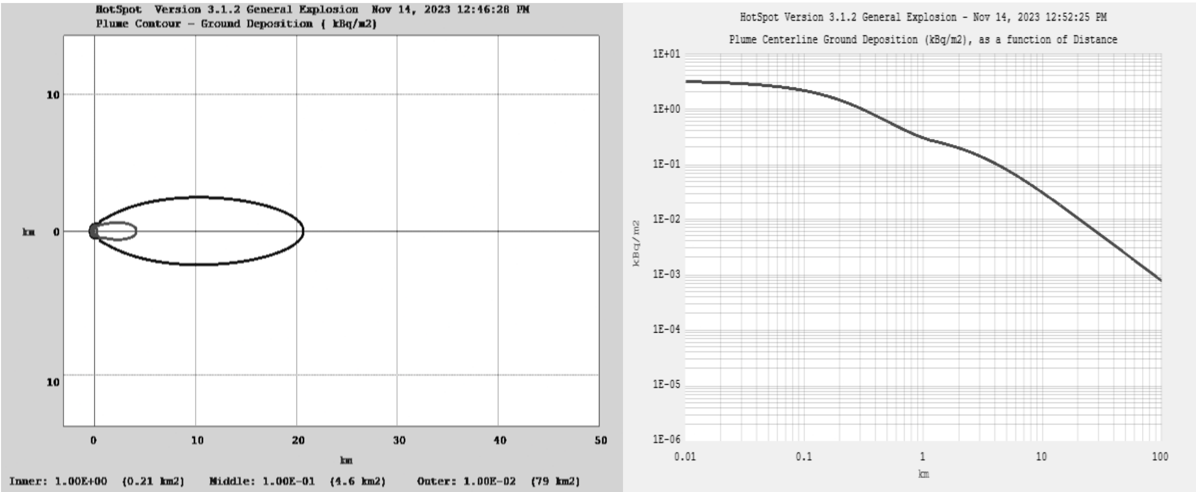


Figure 4: Ground deposition isoconcentration in relation to distance

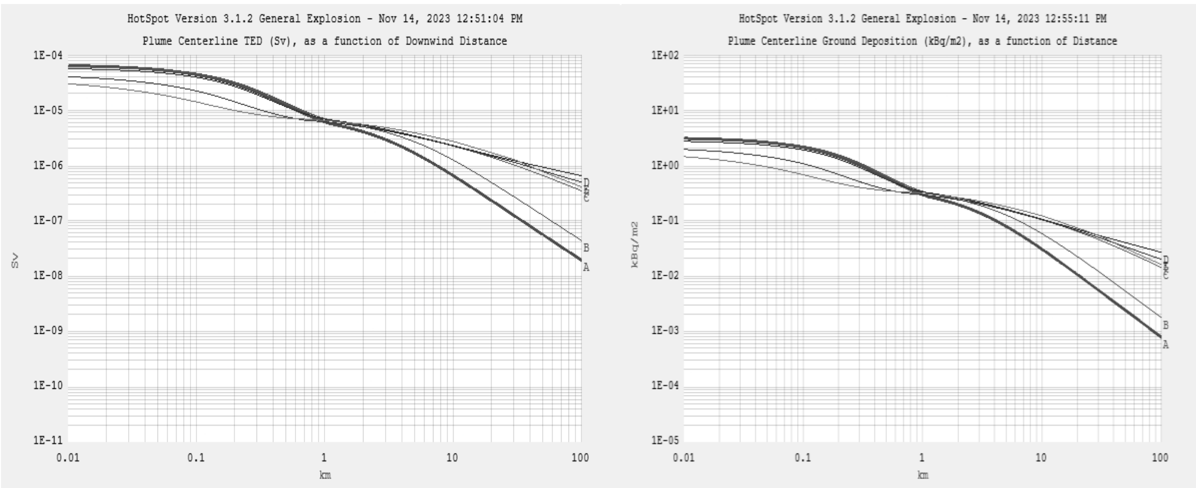


Figure 5: Plume centerline TED (Sv) and ground deposition (kBq/m$^2$) for all stability cases (A-E)

HotSpot enables the visualisation of ground deposition and total effective dose equivalent (TEDE) contours at the release site in Google Earth. Specifically, it facilitates the inclusion of the geographical coordinates (24.0400 N, 89.02499 E) representing the Rooppur Nuclear Power Plant reactor. Figure 6 and 7 displays the georeferencing of TEDE isodoses and ground-deposition concentrations, providing a visual representation of the regions impacted by the dispersion of radionuclides. The figure illustrates that this hypothetical incident will impact a limited number of Upazilas within the Pabna district.

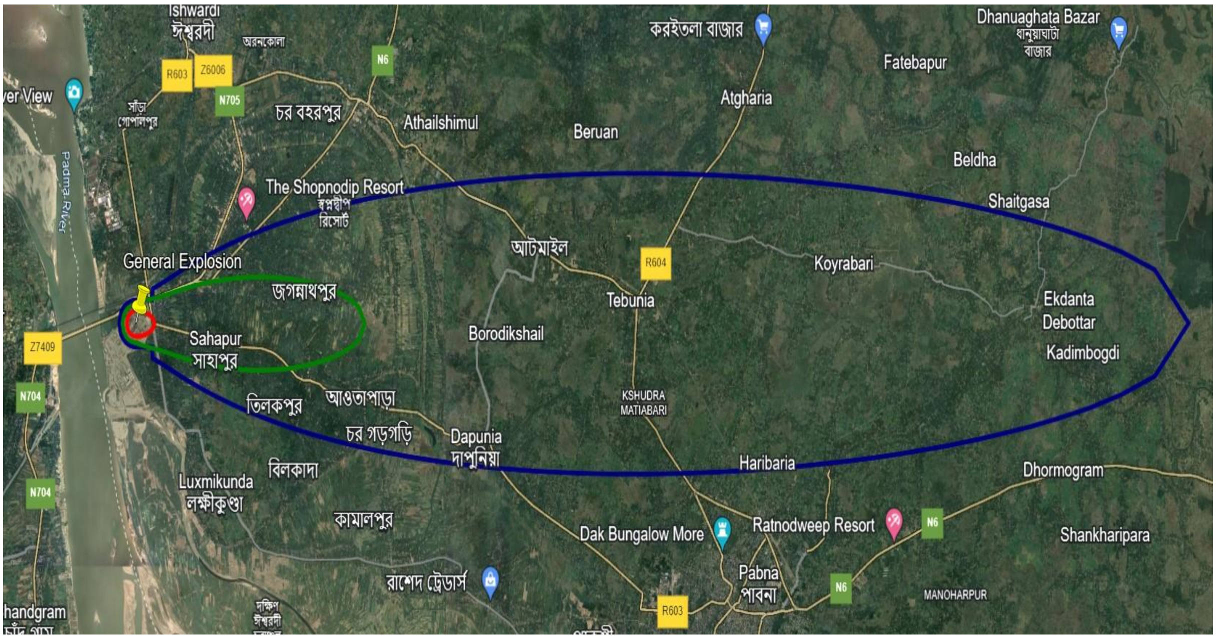


Figure 6: Georeferencing of TEDE

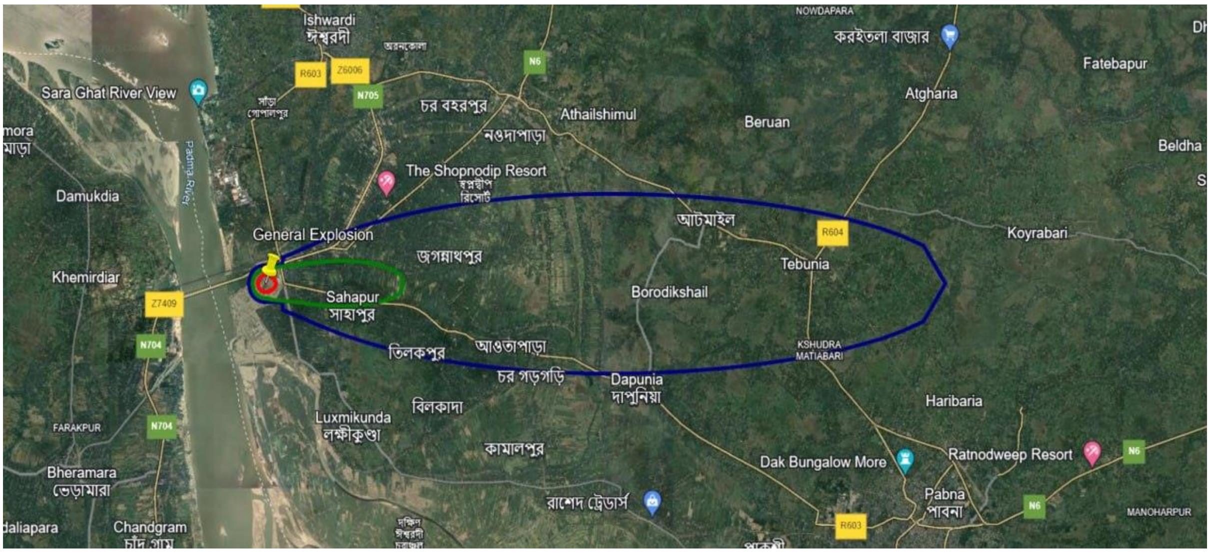


Figure 7: Georeferencing of ground deposition data

The output data derived from the simulation of the general explosion scenario exhibited strong agreement with the data reported in the existing literature. The literature indicated that the average effective doses for individuals involved in the cleanup efforts (liquidators) were approximately 100 mSv. Similarly, residents residing in strictly controlled zones (SCZs), where radioactive caesium contamination exceeded 555 kBq/m$^2$, were found to have an average effective dose of 50 mSv. Lastly, evacuees were observed to have an average effective dose of 30 mSv.

Table 3: HotSpot outputs for the general explosion (GE) scenarios

| **Distance (Km)** | **T E D (sv)** | **Respirable time-integrated air concentration (Bq-sec)/m³** | **Ground surface deposition (kBq/m²)** | **Ground shine dose rate (sv/hr)** | **Arrival time (hour:min)** |
|---|---|---|---|---|---|
| 0.030 | 6.0E-05 | 9.7E+05 | 2.9E+00 | 5.8E-09 | <00:01 |
| 0.100 | 4.5E-05 | 7.2 E+05 | 2.2E+00 | 4.3E-09 | <00:01 |
| 0.200 | 3.0E-05 | 4.9 E+05 | 1.5E+00 | 2.9 E-09 | <00:01 |
| 0.300 | 2.1E-05 | 3.4 E+05 | 1.0E+00 | 2.0E-09 | <00:01 |
| 0.400 | 1.6E-05 | 2.5 E+05 | 7.6E-01 | 1.5E-09 | <00:01 |
| 0.500 | 1.2E-05 | 2.0 E+05 | 6.0E-01 | 1.2E-09 | <00:01 |
| 0.600 | 1.0E-05 | 1.6 E+05 | 4.9E-01 | 9.8E-10 | <00:01 |
| 0.700 | 8.7E-06 | 1.4 E+05 | 4.2E-01 | 8.4E-10 | <00:01 |
| 0.800 | 7.6E-06 | 1.2 E+05 | 3.7E-01 | 7.3E-10 | <00:01 |
| 0.900 | 6.9E-06 | 1.1 E+05 | 3.3E-01 | 6.6E-10 | 00:01 |
| 1.000 | 6.3E-06 | 1.0E+05 | 3.0E-01 | 6.0E-10 | 00:01 |
| 2.000 | 4.1E-06 | 6.6E+04 | 2.0E-01 | 3.9E-10 | 00:02 |
| 4.000 | 2.2E-06 | 3.5E+04 | 1.0E-01 | 2.1E-10 | 00:04 |
| 6.000 | 1.3E-06 | 2.1E+04 | 6.4E-02 | 1.3E-10 | 00:07 |
| 8.00 | 9.1E-07 | 1.4E+04 | 4.3E-02 | 8.4E-11 | 00:09 |
| 10.000 | 6.6E-07 | 1.0E+04 | 3.1E-02 | 6.0E-11 | 00:11 |
| 20.000 | 2.3E-07 | 3.5E+03 | 1.1E-02 | 2.0E-11 | 00:23 |
| 40.000 | 8.0E-08 | 1.2E+03 | 3.5E-03 | 6.4E-12 | 00:47 |
| 60.000 | 4.3E-08 | 6.0E+02 | 1.8E-03 | 3.2E-12 | 01:11 |
| 80.000 | 2.7E-08 | 3.8E+02 | 1.1E-03 | 2.0E-12 | 01:35 |

From Table 3, the distance ranges from 0.030 Km to 80.000 Km has been depicted where total effective dose (TED) values are significanlty decreases from $6.0\times10^{-05}$ Sieverts (Sv) to $2.0\times10^{-08}$ Sieverts (Sv) as the distance increases. Respirable airborne concentration (Bq-sec)/m³ provides the time-integrated activity concentration of respirable radioactive materials in the air in becquerels-second per cubic meter (Bq-sec/$m^3$). This parameter also shows a decreasing trend with increasing distance from the source. Ground surface deposition (Bq/$m^2$) and Ground shine dose rate (Sv/hr) respectively represent the deposited activity on the ground surface in becquerels per square meter (Bq/$m^2$) and the corresponding dose rate due to gamma radiation emitted from the deposited material, measured in sieverts per hour (Sv/hr). Deposition and irradiation both decrease with increasing distance from the source, demonstrating that distance attenuates them. Ground surface deposition values range from $2.9\times1000$ kilo Becquerel per meter square (kBq/$m^2$) to $1.11\times10^{-03}$ kilo Becquerel per meter square (kBq/$m^2$). Ground shine dose rate values are provided which is also decreasing. Arrival time (hour:min) specifies the estimated time for the radioactive plume to reach the specified distances, in hours and minutes. Arrival times range from less than one minute to one hour 35 minutes. This table provides a comprehensive quantitative assessment of the radiological impact in the aftermath of a hypothetical general explosion, as calculated by the HOTSPOT simulation software.

## 4. CONCLUSIONS

- Nuclear power plant in Bangladesh brings significant risks and potential benefits, leading to possible disorder, chaos, and economic impact.
- Potential adverse consequences include environmental degradation and both direct and indirect casualties.
- Simulations indicate widespread impact of hypothetical incidents over large regions.
- Individuals within 34 kilometers of an incident may receive radiation doses of about 0.0001 mSv.
- At a distance of 50 kilometers, radiation exposure could reach the annual dose limit of 1 mSv quickly.
- Evacuation is necessary in the primary region, while others may stay put temporarily.
- The emergency team's onsite presence is initially limited to around 10 minutes but can extend to a few hours with effective management.
- The HotSpot simulation was used for modelling disaster scenarios, estimating radiation doses, and assessing land pollution.
- Simulation results guide decisions on emergency team duration, evacuation, and relocation.
- There's a need for further refinement and enhancement of simulation codes for better accuracy and utility.

**REFERENCES**

Anvari, A., & Safarzadeh, L. (2012). Assessment of the total effective dose equivalent for accidental release from the Tehran Research Reactor. *Annals of Nuclear Energy*, *50*, 251–255. https://doi.org/10.1016/j.anucene.2012.07.002

Dahia, A., Merrcoche, D., Dadda, A., & Cheridi, A. L. (2022). Comparative Radiation Dose Study of a Hypothetical Accident in a Research Reactor. *Kemija u Industriji*, *7–8*. https://doi.org/10.15255/KUI.2021.077

Fairuz, A., & Sahadath, Md. H. (2020). Assessment of the potential Total Effective Dose (TED) and Ground Deposition (GD) following a hypothetical accident at the proposed Rooppur Nuclear Power Plant. *Applied Radiation and Isotopes*, *158*, 109043. https://doi.org/10.1016/j.apradiso.2020.109043

Jafarikia, S., & Feghhi, S. A. H. (2018). Study of in-containment source term behavior for VVER-1000 under LOCA conditions using the IRBURN code system. *Annals of Nuclear Energy*, *112*, 17–29. https://doi.org/10.1016/j.anucene.2017.09.038

Obeng, H. K., Birikorang, S. A., Gyamfi, K., Adu, S., & Nyamful, A. (2021). Assessment of radiological consequence of a hypothetical accident at the Ghana Research Reactor-1 facility based on terrorist attack. *Science Progress*, *104*(4), 003685042110549. https://doi.org/10.1177/00368504211054986

Rennie, G. (n.d.). *HOTSPOT® Health Physics Code*.



View publication stats