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STUDY OF RADIOLOGICAL IMPACT DUE TO ACCIDENTAL RELEASE OF SIGNIFICANT RADIONUCLIDES CONSIDERING VARIOUS WEATHER CONDITIONS FROM THE TRIGA MARK-II RESEARCH REACTOR OF BANGLADESH

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ABSTRACT

From its commissioning, it was required to ensure the nuclear or radiological safety of the BAEC TRIGA Mark-II Research Reactor according to the country-specific regulatory guidance (BAERA) or followed by any international guidance (US NRC or IAEA). It is always important to take protective actions not to commit enough radiological doses. Therefore, the present work focused on the core inventory and radiological dose assessment due to a hypothesized research reactor accident of TRIGA Mark-II at Savar, Dhaka, Bangladesh. The core inventory and source term of five radionuclides (^{137}Cs, ^{131}I, ^{133}Xe, ^{85m}Kr, and ^{90}Sr) were studied using the ORIGEN 2.1 code until December 2021. These radionuclides were chosen due to their high emission characteristics from a nuclear accident. The dose values of TED, ground deposition, and organs were calculated for an 80 km radius from the reactor site using the HotSpot 3.1.2 code and meteorological data of six seasons of Bangladesh. The assessed dose values are compared and it is shown that dose values in the rainy season are highest due to the rainout coefficient. The other five seasonal TEDE data show similar dose patterns and are also high enough to the permissible limit of dose values. So, regardless of the time of year, if an accident occurs, it is necessary to immediately take preventive radiological measures based on the local authority emergency response plan.

Keywords: *Radiological safety, Research reactor, HotSpot 3.1.2, Nuclear accident.*

1. INTRODUCTION

Safety has been a paramount concern since the early stages of nuclear reactor development. Nuclear infrastructure, such as nuclear reactors, can cause potential radiation risks to people and the environment. In the event of a nuclear disaster, an uncontrolled emission of radiation into the environment could pose a major radiological threat to humans and other creatures. For example, the nuclear reactor accident at Chernobyl in 1986 and Fukushima in 2011 are regarded as the most disastrous events in nuclear power plant history. Both of these nuclear accidents released a significant number of radionuclides into the atmosphere. Therefore, it is crucial to conduct a radiological dose assessment in the event of a nuclear accident, as nuclear and radiological safety considerations are essential for nuclear reactors [1–2]. Radiological safety analysis for imaginary nuclear accidents under various weather conditions would be critical to ensuring the safety of nuclear reactors with regard to human health and safety [3–4]. Furthermore, it is imperative to establish an emergency preparedness program that provides the authority with comprehensive information and robust protective measures to reduce the risk of radiation. Following an accident's emission of radioactive elements, the human body may absorb the equivalent dose from an external or internal source. The classification comprises two components: the total effective dose equivalent (TEDE) and the committed effective dose equivalent (CEDE). The EDE comes from external exposures such as submersion, ground shine, and re-suspension, while the CEDE comes from internal exposures such as breathing it in. It can be concluded that TEDE provides a realistic estimate of total dosage from all relevant releasing routes [5–6]. B. Cao et al. [6] estimated the radiation dose in a hypothetical AP1000 SGTR accident using HotSpot code 3.03 and examined its potential spread through the atmosphere. Using HotSpot 3.0 and HYSPLIT 4 safety analysis codes, Ahangari et al. performed a radiological dose analysis for the Tehran research reactor under assumed accidental conditions [7]. Raza and Iqbal investigated Pakistan Research Reactor-1 in a similar manner [8]. M. A. Malek et al. used a fictitious accident scenario involving the TRIGA Mark-II research reactor at the Atomic Energy Research Establishment (AERE) in Savar, Bangladesh, to calculate the radiological dose that ^{131}I, ^{132}I, ^{133}I, ^{134}I, and ^{135}I released from the reactor would deposit on plants, animals, milk, and the ground [9]. S. N. A. Sulaiman evaluated the atmospheric release and core inventory of the Puspati TRIGA reactor [10].

This study aimed at the assessment of TEDE and other organ doses, taking into account the postulated accident of the country's one and only TRIGA Mark-II research reactor at AERE, Savar, Dhaka. The radiological dosage is accounted for the radionuclides of ^{137}Cs, ^{131}I, ^{90}Sr, ^{85}Kr, and ^{133}Xe in this context, as these nuclides are responsible for a significant portion of the dose. Under the present study we assessed the dose using the user-friendly HotSpot 3.1.2 code [11].

3. MATERIALS AND METHODS

3.1. SOURCE-TERM ESTIMATION

The source term is an essential component of calculating a nuclear reactor's radioactive content into the atmosphere. The activity A_i (t) of an isotope i at time t following the start of irradiation (t = 0), with a fission yield of γ_i and a decay constant of λ_i, after being irradiated for period T in P (megawatts off thermal power), can be approximated as [12].

$$A_i(t) = 0.82\gamma_i P\left(1 - e^{-\lambda_i.T}\right) \times e^{\lambda_i(t-T)} \quad (1)$$

Radiological doses outside the nuclear facility can only be produced by radionuclides that have a high degree of mobility and a sizable volume that can be released from the reactor building's stack.

In this work, the radiological source term and fission product inventories of all fuel elements were obtained using the ORIGEN 2.1 computer code, and the inventories of each fuel element were analyzed for a reactor operation from September 14, 1986 to December 2021. For source term calculations, it was considered that the reactor was operating at its full power (3 $MW_{th)}$. The operation was evaluated on a continuous basis to accomplish 832.58 MWD of burn-up, which corresponded to an average of 15% of the entire initial mass of ^{235}U in the core at the time of the postulated accident. The core activity was 2.3×10^{17} Bq, and the total activity released in the atmosphere was 1.79×10^{17} Bq. The release fraction of ^{137}Cs, ^{131}I, ^{133}Xe, ^{85m}Kr, and ^{90}Sr were taken to be 0.3, 0.4, 1, 1, 0.05, and 0.003, respectively. Table 1 shows the inventories of ^{137}Cs, ^{131}I, ^{133}Xe, ^{85m}Kr, and ^{90}Sr radionuclides in the reactor core, along with their core release fractions, and activity released in the atmosphere.

Table 1. The core inventory and source term of radionuclides ^{137}Cs, ^{131}I, ^{90}Sr, ^{85}Kr, and ^{133}Xe at 3MW_{th} power level for 832.58MWD burn-up of research reactor operation.

Name of Radionuclides	Fission Yield (%)	Half-lives (days)	Core Inventory (Bq)	Source term (Bq)
^{137}Cs	0.0622	11377.05	2.02×10^{16}	6.06×10^{15}
^{131}I	0.0289	0.02	5.70×10^{16}	2.28×10^{16}
^{90}Sr	0.058	28.9	1.93×10^{15}	3.87×10^{13}
^{133}Xe	0.066	3934.7	1.26×10^{17}	1.26×10^{17}
^{85m}Kr	0.00271	5.24	2.48×10^{16}	2.48×10^{16}

3.2. ACCIDENT ASSUMPTION

This research assumed that a plane crash had caused catastrophic damage to the building. The fuel rods were completely ruined. As a result, the reactor core discharged most of the fission products into the atmosphere. After completely dismantling the reactor building, we measured the release height, starting at 0 meters. We used the ORIGEN 2.1 code to determine the activity of ^{137}Cs, ^{131}I, ^{90}Sr, ^{85}Kr, and ^{133}Xe, taking into account the aforementioned assumptions. We calculated the source term (NRC 2000) using the release fractions from the US-NRC regulatory handbook, as shown in table 1. Table 1 also displays the estimated activity and release rates for the 832.58 MWD operation at a 3 MWth power level.

3.3. METEOROLOGICAL DATA

We obtained the meteorological data for the past 30 years (1993–2022) from the Bangladesh Meteorological Department (BMD), Dhaka Station, situated approximately 40 km from the reactor site. At present, the AERE campus lacks a meteorological station. Typically, the wind velocity in the appropriate direction and stability class determine the dispersion of radionuclides as a function of downwind distance. Consequently, the radioactive concentrations will diminish as the distance from the source to the downwind increases. Figs. 1-6 illustrate the wind rose of the meteorological data, and we estimated the percentages of frequency and velocities in the 16 cardinal directions using meteorological data from six seasons over the past 30 years (1993–2022). In the autumn, late autumn, moist spring, summer, and winter seasons, the highest frequency directions are South, North, South, South, and West, respectively. And, 2.55 m/s, 2.16 m/s, 2.84 m/s, 3.41 m/s, 3.25 m/s, and 2.67 m/s are the average wind velocities during those seasons. The site's leading stability class is "B" for all seasons, as indicated by this outcome.

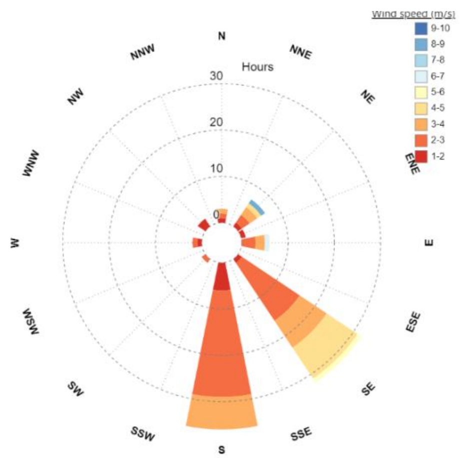

Fig. 1. The wind rose of Autumn, Dhaka, (1993-2022).

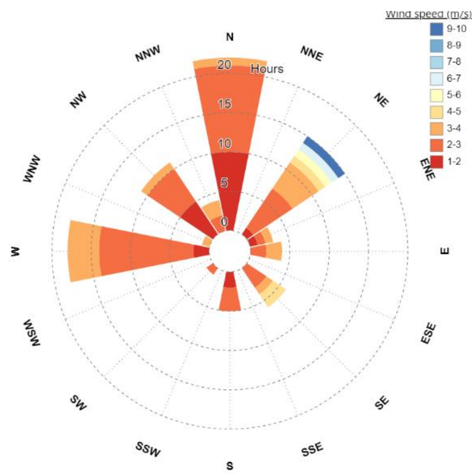

Fig. 2. The wind rose of late autumn, Dhaka, (1993-2022).

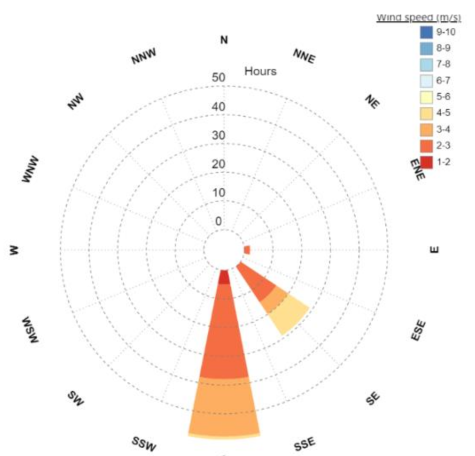

Fig. 3. The wind rose of Rainy, Dhaka, (1993-2022).

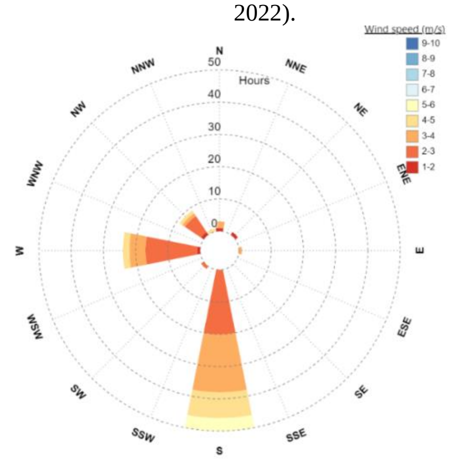

Fig. 4. The wind rose of Springs, Dhaka, (1993-2022).

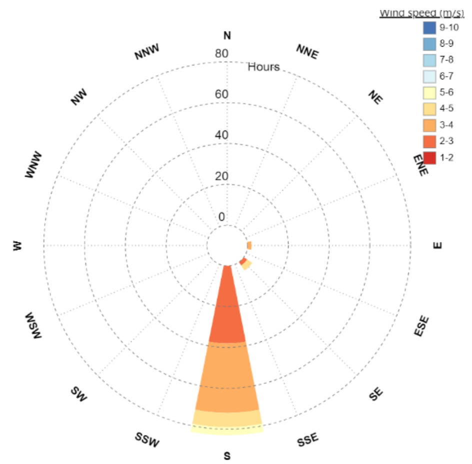

Fig. 5. The wind rose of Summer, Dhaka, (1993-2022).

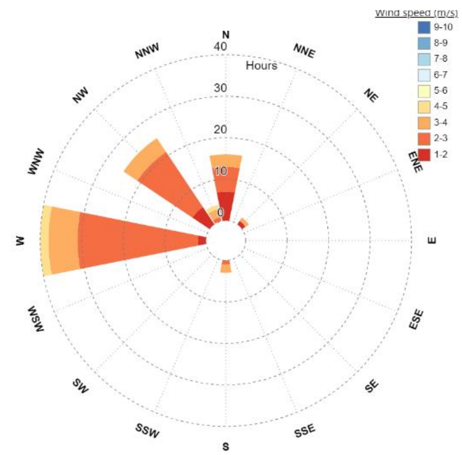

Fig. 6. The wind rose of Winter, Dhaka, (1993-2022).

4. RESULTS AND DISCUSSION

4.1. RESULTS

The present research evaluated the radiological dose using the health physics code HotSpot 3.1.2. The maximum doses were calculated for up to an 80 km radius around the research reactor. In addition, as part of the source term assessment, an estimate for radioactive material release into the atmosphere was made. Using HotSpot 3.1.2 code, the maximum dose distributions were evaluated for five major dose contributory radionuclides. By analyzing the past 30 years (1993-2022) meteorological data of Dhaka and released nuclide activity, we got various dose limits for different seasons using the HotSpot 3.1.2 codes.

In this work, radiological dose estimation and their effect will be analyzed for six seasons in Bangladesh. The six seasons of Bangladesh are autumn, late autumn, rainy, spring, summer, and winter. The autumn season typically spans from mid-August to mid-October in this region. During this period, the weather is characterized by relatively low humidity and moderate rainfall. Late Autumn in this region typically spans from mid-October to mid-December and is characterized by lower humidity levels compared to the hot and humid summer months. The rainy season in Bangladesh usually occurs from mid-June to mid-August. Unlike the hot and humid summer months, the temperature during this season is relatively moderate. The humidity levels remain high, and strong winds often accompany the rain. The spring season in the specified region lasts from mid-February to mid-April and is characterized by relative humidity ranging from 50% to 70%. The summer season in Bangladesh is from mid-April to mid-June. Winter, the fifth season in Bangladesh, occurring from mid-December to mid-February, is known for its cold weather.

Over the past 30 years, the prevailing wind direction during these seasons has been from the south, north, south, south, south, and west with an average speed of 2.55 m/s, 2.16 m/s, 2.84 m/s, 3.41 m/s, 3.25 m/s, and 2.67 m/s, those are in Fig. 3 to Fig. 8. In this case, the stability class for all seasons is assumed "B", according to Pasquill's stability class.

It is seen from Fig. 7 to Fig. 12 that all seasonal TED dose values are maximum at 0.03 kilometer and the dose values are 7.4×10^{02} Sv, 8.7×10^{02} Sv, 8.30×10^{02} Sv, 5.50×10^{02} Sv, 5.80×10^{02} Sv and 7.10×10^{02} Sv in the autumn, late autumn, rainy, spring, summer, and winter season, respectively. The TED for all seasons shows a linearly decreasing manner with distance except the TED for the rainy season. It shows a sharply decreasing pattern after a 10 km distance due to the rainout coefficient, as shown in Fig. 11. All seasonal TED covers a long-distance area with a high dose value. After that, they fall below the permissible limit to the general public. The TED fall below 1 mSv after 28.5 km, 27km, 10 km, 28 km, 30 km, and 29.5 km, respectively.

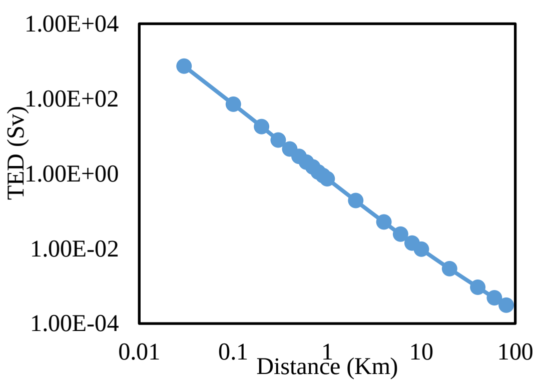

Fig. 7. Graphical representation of TED (Sv) as a function of distance (km) in the autumn season.

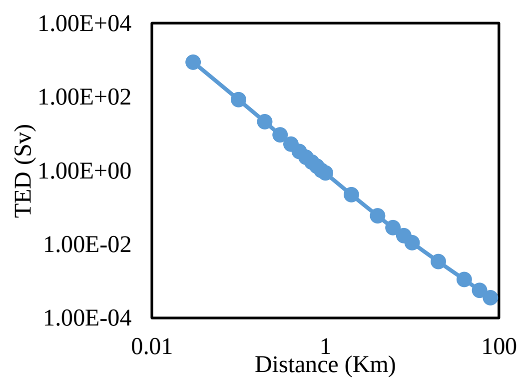

Fig. 8. Graphical representation of TED (Sv) as a function of distance (km) in the late autumn season.

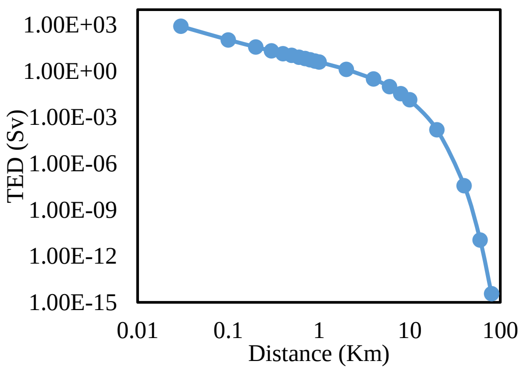

Fig. 9. Graphical representation of TED (Sv) as a function of distance (km) in the rainy season.

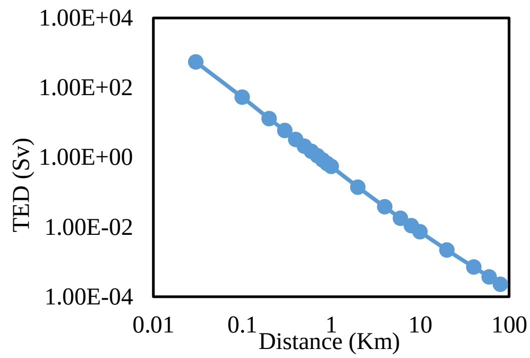

Fig. 10. Graphical representation of TED (Sv) as a function of distance (km) in the spring season.

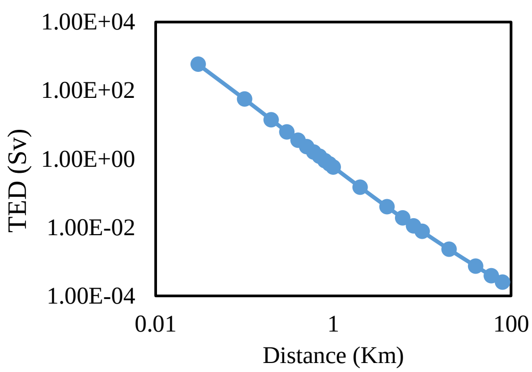

Fig. 11. Graphical representation of TED (Sv) as a function of distance (km) in the summer season.

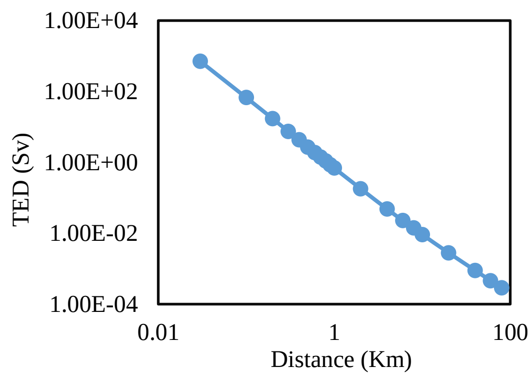

Fig. 12. Graphical representation of TED (Sv) as a function of distance (km) in the winter season.

In this study, we have considered three contour lines to determine the affected area: the 50 mSv (inner), 10 mSv (middle), and 1 mSv (outer) contour lines. These lines help to designate the zones for the evacuation area, the sheltering area, and the annual permissible dose-exceeding area for the general public, respectively. From Fig. 13, it is seen that the evacuation and sheltering areas are higher in the rainy seasons. However, the evacuation and sheltering areas are approximately similar in the all other seasons.

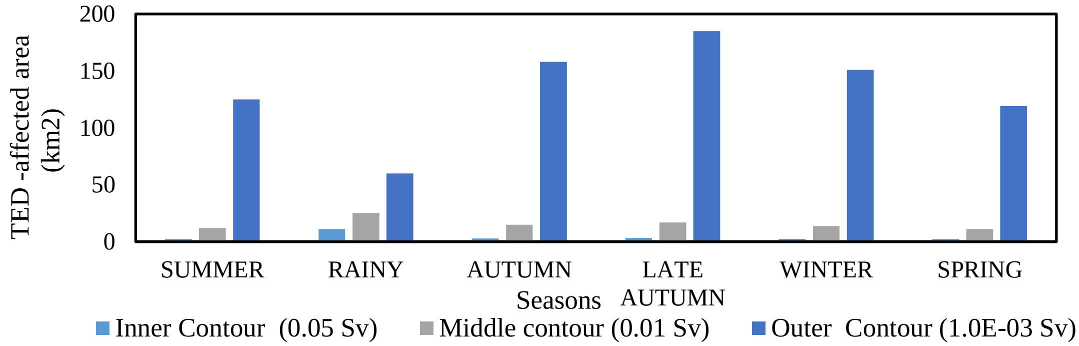

Fig. 13. TED-affected area (km^2) comparison regarding seasonal weather variations.

Organ dose graphs are shown in Figs. 14-19. It is seen that some organs, such as skin, surface bone, thyroid, and esophagus are always maximum dose absorbers. The Thyroid dose also covers long distances with higher dose values for all seasons. The Thyroid dose is also maximum at 0.03 km and falls below 50 mSv after 20 km, 20 km, 8 km, 18 km, 19 km, and 18 km in the autumn, late autumn, rainy, spring, summer, and winter seasons, respectively.

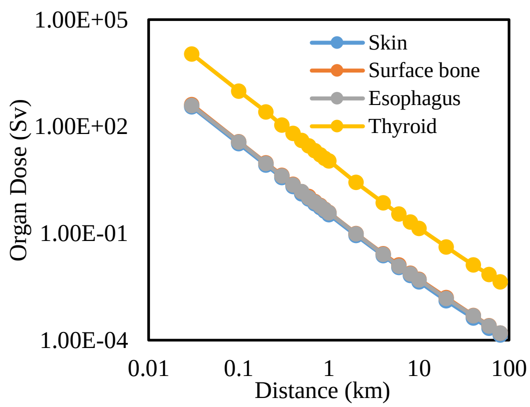

Fig. 14. Graphical representation of organ doses (Sv) as a function of distance in the autumn season.

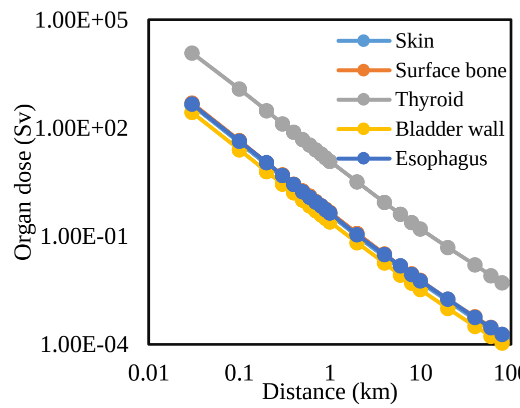

Fig. 15. Graphical representation of organ doses (Sv) as a function of distance in the late autumn season.

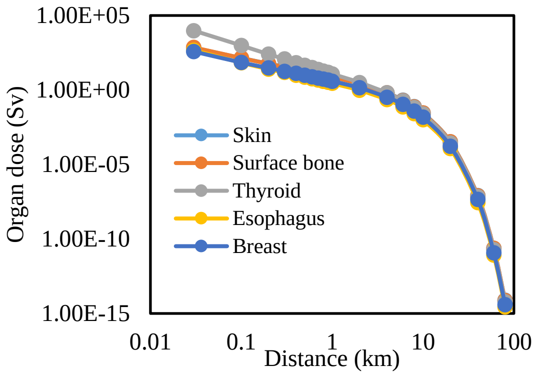

Fig. 16. Graphical representation of organ doses (Sv) as a function of distance in the rainy season.

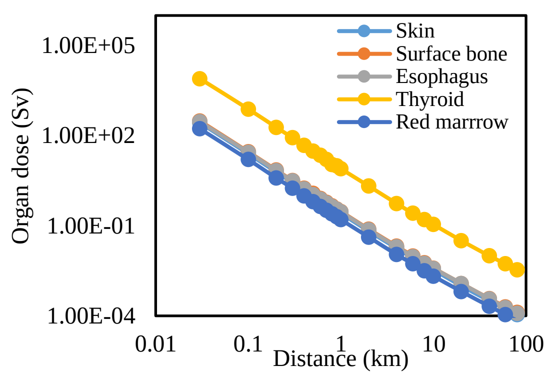

Fig. 17. Graphical representation of organ doses (Sv) as a function of distance in the spring season.

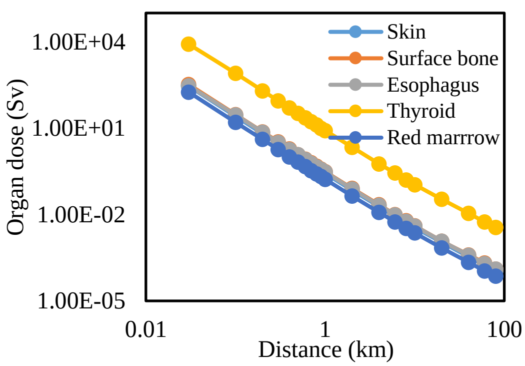

Fig. 18. Graphical representation of organ doses (Sv) as a function of distance in the summer season.

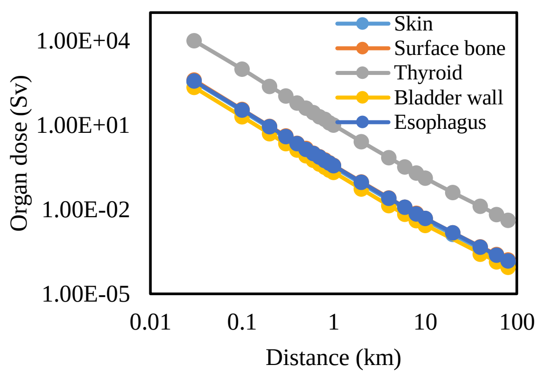

Fig. 19. Graphical representation of organ doses (Sv) as a function of distance in the winter season.

Similar to TED, organ dosage values exhibit drastically diminishing behavior with distance. Organ dosages decrease dramatically after 10 km.

4.2. DISCUSSION

In this analysis, six seasonal weather data for 30 years of Bangladesh have been considered. According to the weather data, the wind comes from the south most of the time, and the average wind velocities are similar except for spring and summer. The stability class for all seasons is selected "B" for daytime according to Pasquill's stability class. The TED, Thyroid, and some major organ dose are analyzed here. It is seen that TED doses for all seasons cover very longer distances. The TED drops below the allowable exposure limit for the general population after a maximum of 30 km. The TED shows only sharply decreasing behavior with distance in rainy season except in other seasons. The TED dose on rainy is higher at close distances and decreases rapidly due to the rainout co-efficient of the rainy season. Among the organ doses the Thyroid doses are maximum in all seasons, and it also covers very longer distances. It covers the distances with the higher dose values above the permissible limit are 20 km, 20 km, 8 km, 18 km, 19 km, and 18 km in the autumn, late autumn, rainy, spring, summer, and winter seasons, respectively. Because the TRIGA Mark-II research reactor is located in a residential and industrial region outside of it, long-distance protective actions such evacuation, sheltering, and iodine tablet (KI) are required if an accident occurs.

5. CONCLUSION

To lessen the societal and financial loss after a nuclear or radioactive disaster, good risk management is essential. This includes implementing emergency response plans and providing education to individuals and communities on how to respond in the event of an emergency. Therefore, we carried out a core activity and radiological dose assessment for a hypothetical accident involving the TRIGA Mark-II research reactor in Bangladesh. The study examines the reactor building's core activity, the source term of radionuclides ^{137}Cs, ^{131}I, ^{90}Sr, ^{85}Kr, and ^{133}Xe into the atmosphere, and the impact of these radionuclides have on the surrounding areas of the reactor facility. In this work, we utilized local weather data to determine the dose values. We found that the maximum TED and thyroid dose values exceed the allowable limit in all seasons. The outside areas of the AERE campus are industrial and residential. So, according to early preventative action standards, it is required to take precautions such as evacuation, sheltering, and taking iodine-based medicines in those areas.

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