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Radiological Concentration Distribution of ^{131}I, ^{132}I, ^{133}I, ^{134}I, and ^{135}I Due to a Hypothetical Accident of TRIGA Mark-II Research Reactor

M. A. Malek[1], K. J. A. Chisty[2], M. M. Rahman[3]
[1]Department of Electrical and Electronic Engineering, Green University of Bangladesh, Dhaka, Bangladesh
[2]Department of Electrical and Electronic Engineering, European University of Bangladesh, Dhaka, Bangladesh
[3]Energy Institute, Atomic Energy Research Establishment, Dhaka, Bangladesh
Email: malekphy@gmail.com, kja_chisty@yahoo.com, mizanrbd@gmail.com

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ABSTRACT

The present work gives a methodology for assessing radiological concentration of ^{131}I, ^{132}I, ^{133}I, ^{134}I, and ^{135}I due to a hypothetical accident of TRIGA Mark-II research Reactor at AERE, Savar, Bangladesh. The concentrations were estimated through different pathways like ingestion of vegetation, milk, and meat from air and ground deposition. The maximum air concentrations for all 16 directions were found at 110 m distance from the core of the reactor and it was found to be highest in the southern (S) direction. The maximum ground concentration occurred immediately just after the accident in different directions. In all pathways, the most concentration was found to be in S-direction. The concentrations in vegetation of ^{131}I, ^{133}I, ^{135}I were significant, while no concentrations of ^{132}I and ^{134}I were observed. The concentration in vegetation for ^{131}I was found to be highest than all other isotopes of iodine. The concentrations of ^{133}I were found to be higher and concentrations of ^{134}I were observed to be lower in both milk and meat compared to other radio isotopes of iodine. In the case of a radiological accident, the results of the present study will be a valuable guide for adopting radiological safety measures for radiation protection against the ingestion of vegetables, milk and meat from around the research reactor at AERE, Savar, Bangladesh.

Keywords: Concentration; Effective Stack Height; Pathway; S-Direction; TRIGA Mark-II

1. Introduction

Atmospheric diffusion and radiation concentration calculations for accidental releases of radioactive gases and volatiles are an important contribution to licensing requirements for the selection of site for a nuclear reactor. The reactor-operating license is obtained from local regulatory authorities in accordance with internationally adopted criteria [1].

Nuclear reactors, specially research reactors, do not release any significant quantity of radioactive material to the atmosphere under normal operating conditions. However, a significant fraction of the radionuclide inventory in the core may be released to the atmosphere under accident conditions with severe core damage. In the case of a hypothetical accident of research reactor, radionuclides that are predictable to be released through the stack, can cause direct radiation exposure of the public in the downwind direction and can also be deposited on the ground and vegetation resulting in exposure through different pathways such as external irradiation, inhalation, ingestion etc. [2,3], when cows eat vegetation, milk and meat become contaminated. Immediately after an accident, isotopes of iodine such as ^{131}I, ^{132}I, ^{133}I, ^{134}I, and ^{135}I presents the most serious radiological hazards [4]. The main doses concerns are those to thyroid due to external irradiation, inhalation and ingestion of radioiodines.

To evaluate doses, measurement of activity concentration of radionuclides in different pathways is necessary. An attempt has therefore been made in this work to find out the concentration in vegetation, milk and meat due to deposition of ^{131}I, ^{132}I, ^{133}I, ^{134}I, and ^{135}I considering hypothetical accident of TRIGA MARK-II research reactor at AERE, Savar. Radionuclides can be deposited on soil either by direct deposition from the atmosphere or from the use of surface water for irrigation. When there is a canopy of vegetation, radionuclides can reach the soil through leaf fall, leaching, wash-off, herbivore excretion and trampling [5].

Different assumptions and methodologies have been taken into account for assessing concentration suggesting the necessity of site-specific data. Recently IAEA published generic methodologies for use in assessing the radiological consequence due to the releases of radioactive

materials in the environment, [5,6]. A computational code has been developed based on these methodologies and a hypothetical accident scenario to predict the concentration of ^{131}I, ^{132}I, ^{133}I, ^{134}I, and ^{135}I in vegetation, milk and meat. An IAEA document on research reactors used 100%, 40% and 1% release fractions for noble gases, halogens and particulates, respectively [6]. In this work, we have calculated only the release of radioactive iodine which is volatile, and 40% release fraction was considered. The input parameters like wind speed and frequency at different direction, average temperature needed in the calculation have been collected from Bangladesh Meteorological Department for the AERE site. Other essential parameters needed in the calculation have been taken from elsewhere [5].

2. Source Term and Accident Scenario

2.1. Source Term Calculation

The radiological source term describes the amount of the nuclides which are released to the containment. A number of mathematical expressions can be applied to calculate the amount of fission products in the research reactor core as a function of irradiation time. An approximate formula giving activity $A_i(t)$ of an isotope i at time t after the start of irradiation ($t = 0$) whose fission yield is γ and its decay constant is λ_i irradiated for a time period T in P (megawatts of thermal power) can be written [6] as:

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

Radiological doses outside the reactor facility can be caused only by radionuclides with a high degree of mobility. The isotopic data considered here is limited due to volatile group which is likely to be released in significant quantities in the event of fuel melting with halogens, volatiles (e.g. iodine); the most important contributors. A considerable amount of radionuclides can be released from the stack of the reactor building.

2.2. Release Rate Calculation

Source analysis addresses the problem of deriving the source terms that determine the rate at which residual radioactivity is released into the environment. This is termed as release rate. The release rate of the radionuclides from stack is determined by the concentrations of the radionuclides present, the ingrowth and decay rates of the radionuclides, fraction released from fuel to building, the geometry of the containment, the leak rate parameter and overall the source term.

The total activity of isotope i released over time τ, $Q(\tau)$, is obtained from the following Equation [6] as:

$$Q_i(\tau) = F_p F_b A_i(t) \frac{\lambda_l}{\lambda_l + \lambda_r}\left[1 - e^{-(\lambda_l + \lambda_r)\tau}\right] \quad (2)$$

where F_P is the fraction released from fuel to building, F_B is the fraction remaining airborne and available to be released from the building to the atmosphere, λ_i is the source term, λ_l is the leak rate parameter, sec^{-1}, and λ_r is the radioactive decay constant, sec^{-1}.

2.3. Assumptions Made in the Calculation

In case of radiological assessment, source term is a very vital parameter. The radiation received by the population around the TRIGA reactor facility is directly dependent on this parameter. Some realistic assumptions have been made for doing the calculation of the present work. These are given below:

- The reactor was operated at full power, *i.e.* 3 MW (t);
- Time after the start of irradiation: 10 days;
- Continuous operation at full power: 10 days;
- Radionuclide release time into the atmosphere from stack: 2 hours after the accident;
- Radionuclides considered for radiological concentration assessment into the environment around the reactor building: ^{131}I ($T_{1/2}$ = 8.04 days), ^{132}I ($T_{1/2}$ = 2.30 hrs), ^{133}I ($T_{1/2}$ = 20.8 hrs), ^{134}I ($T_{1/2}$ = 0.876 hrs) and ^{135}I ($T_{1/2}$ = 6.61 hrs);
- Fraction release [7]: Iodine: 40% of the equilibrium radioactive iodine (^{131}I, ^{132}I, ^{133}I, ^{134}I, ^{135}I) inventory developed from maximum fuel power operation of the core are immediately available for leakage to the reactor building in the direct proportion to percent of fuel failure [7];
- Leak rate parameter, $\lambda_1 = 1.157 \times 10^{-7}$ sec^{-1}. *i.e.*, 1%/day [5].

Considering the above assumptions, the activity of iodine (^{131}I, ^{132}I, ^{133}I, ^{134}I and ^{135}I) was calculated considering the above assumptions and using Equation (1). The fission yields of the corresponding radionuclides were obtained as the fission fragment of the total product by neglecting the filter and shielding efficiency. A constant reactor power of 3 MW(t) is an acceptable approximation for the irradiation. The fission product inventory would be maximum corresponding to the infinite irradiation time. The calculated activity released rate of ^{131}I, ^{132}I, ^{133}I, ^{134}I and ^{135}I for 10 days operation at 3 MW(t) power level are given in **Table 1**. The Table illustrates that the total activity in the reactor core and released rate from containment to environment through the stack for ^{131}I, ^{132}I, ^{133}I, ^{134}I, and ^{135}I are comparable with one another. This is due to the similarity of fission yields and fraction of release for these radionuclides.

3. Atmospheric Dispersion and Radiological Concentration Calculation Models

3.1. The Gaussian Plume Model (GPM)

In the case of an accident, the escaped fission products

Table 1. Calculated fission product inventory for 10 days operation at 3 MW(t) power level.

Radionuclides	Fission yield	Total activity in core (C_i)	Released rate (Bq/sec)
^{131}I	0.0289	4.074×10^4	6.965×10^7
^{132}I	0.054	6.06×10^4	8.960×10^7
^{133}I	0.026	5.982×10^4	1.008×10^8
^{134}I	0.047	2.376×10^4	2.812×10^7
^{135}I	0.050	9.973×10^4	1.622×10^8

from reactor hall generally disperse in the surrounding atmospheric environment through a stack of the reactor as a radioactive smoke plume. The dispersion of radioactive plume to the atmosphere depends strongly on the atmospheric conditions such as temperature, wind frequency, direction, speed and humidity of the atmosphere. Gaussian plume model is widely applied to calculate atmospheric dispersion in the atmospheric environment. This model assuming that a Gaussian distribution in both lateral and vertical directions can be described as [6]

$$\chi(x,y,z)=\frac{Q_i}{2\pi\sigma_y\sigma_z u_a}\mathrm{e}^{\left(\frac{-y^2}{2\sigma_y^2}\right)}\left\{\mathrm{e}^{\left[-\frac{(H-Z)^2}{2\sigma_z^2}\right]}+\mathrm{e}^{\left[-\frac{(H+Z)^2}{2\sigma_z^2}\right]}\right\} \quad (3)$$

where $\chi(x,y,z)$ is the radionuclide concentrations at point (x,y,z) (Bq/m^3); Q_i is source strength or release rate (Bq/s), u_a is the wind speed at the height of the stack (m/s), H is the stack height (m), σ_y and σ_z are the lateral and vertical dispersion parameters (m), depending on stability class. For radiological concentration assessment ground level concentration is required and therefore, z can be assumed to be zero and Equation (3) can be written as

$$\chi(x,y,z)=\frac{Q_i}{\pi\sigma_y\sigma_z u_a}\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left\{\exp\left[-\frac{H_{\mathrm{eff}}^2}{2\sigma_z^2}\right]\right\} \quad (4)$$

where H_{eff} is the stack height (m). The average concentration for release that occurs over a period of time can be calculated by applying the above equation.

3.2. Effective Stack Height (ESH)

If the effluent has a significant exit velocity (or if it is at a high temperature), it will rise to a level higher than the actual stack height. The effective stack height, therefore, is the sum of the actual stack height (H) plus a factor that accounts for the exit velocity and/or the temperature of the effluent gas as [8]

$$H_{\mathrm{eff}}=H+D\left(\frac{v}{u_a}\right)^{14}\left(1+\frac{\Delta T}{T}\right) \quad (5)$$

where D is the outlet stack diameter (m), v is the exit effluent velocity (m/s), ΔT is the difference between ambient and effluent gas temperatures, T is the absolute temperature of the effluent.

For a research reactor like a TRIGA Mark-II at AERE, Savar, the temperature difference, ΔT can be considered to zero because of active operation of the ventilation system.

3.3. Average Wind Speed at ESH

Usually, meteorological data for wind speed and direction are measured at a 10 m height. This speed needs to be converted into an effective stack height applying the following relationship [3,9] as

$$u=u_z\left(\frac{H_{\mathrm{eff}}}{z}\right)^m \quad (6)$$

where u_z is the speed at ground level at a height z = 10 m and m is the wind coefficient depending on underlying surface and diffusion category.

3.4. Air Concentration of Radionuclides and Gaussian Diffusion Factor

In this case the sector averaged form of the GPM may be used with the following simplifying assumptions:

1) A single wind direction and frequency for each air concentration calculation;

2) A single long term average wind speed for each direction;

3) A neutral atmospheric stability class (Pasquill-Gifford stability class B) [5].

Air concentration of a radionuclide can be calculated based on the above mentioned assumptions by using the Equation [5]

$$C_A=\frac{P_p F Q_i}{u_a}\exp\left(-\lambda_i\frac{x}{u_a}\right) \quad (7)$$

where C_A is the ground level air concentration at downwind distance x in sector p (Bq/m^3); P_p is the fraction of the time that the wind blows towards the receptor of interest in sector p; u_a is the geometric mean of the wind speed at the height of release (m/s); F is the Gaussian diffusion factor, appropriate for the height of release H_{eff} and the downwind distance x being considered (m^{-2}); Q_i is the average annual discharge rate for radionuclide i (Bq/s); λ_i is the rate constant for radioactive decay of radionuclide i.

The Gaussian diffusion factor F as a function of downwind distance x for a fixed value of H_{eff} can be estimated using the 22.5˚ sector averaged form of the Gaussian plume model is given by [6]

$$F = \frac{16}{\sqrt{2\pi^3}} \times \frac{\exp\left[-\left(\frac{H_{\text{eff}}^2}{2\sigma_z^2}\right)\right]}{x\sigma_z} \quad (8)$$

where σ_z is the vertical diffusion parameter (m).

These expressions are appropriate for dispersion over comparatively flat territory without pronounced dills or valleys which is practically appropriate for our research rector site. The territory is assumed to be covered with pastures, forests and small villages. The value of σ_z can be calculated on the basis of the following relationship [5]

$$\sigma_z = E \cdot x^G \quad (9)$$

where E and G are the two parameters depending on the stability class and on the effective stack height, and x is the downwind distance.

Here for stability class "*B*" E = 0.127 and G = 1.108 for release height of 32.36 m at various downwind distance x m [10-12] was considered.

3.5. Group Deposition

The radioactive material may be removed from the plume by the action of rain or snow interacting with it. In general, the process can be assumed to remove radionuclides uniformly through the entire vertical extent of the plume. The removal rate at any distance from the source corresponds to the total amount of radio nuclides reaching that distance.

It can also be removed from the plume by dry deposition. The rate at which material is deposited from the plume will depend on the nature of the airborne material and the underlying surface and can be estimated using the concept of a deposition velocity or specifically, deposition coefficient. The deposition coefficient is defined as the ratio of the amount of activity deposited on the ground per unit time and the ground level air concentration. For simplified assessment purposes, the following relationship is used as

$$d_i = \left(V_d + V_w\right) C_A \quad (10)$$

where d_i is the total daily average deposition rate on the ground of a given radionuclide i from both dry and wet processes, including deposition either on to impervious surfaces or on to both vegetation and soil (Bq·m^{-2}·d^{-1}); V_d is the dry deposition coefficient for a given radionuclide (m/d); V_w is the wet deposition coefficient for a given radionuclide (m/d).

The values of V_d and V_w for radionuclides are quite variable. They depend on such factors as the physical and chemical form of the radionuclide, the nature of the deposition surface, meteorological conditions and, in the case of V_w, the precipitation rate [13]. It has been recommended that a total deposition coefficient, V_T (=V_d + V_w). For deposition of aerosols and radioactive gasses and radioactive gasses, V_T = 1000 m/d may be used for screening purposes [14]. This value of V_T was found to be consistent with values for radioiodine and radiocesium from the accident at the Chernobyl nuclear power station in 1986. Deposition rate can be used to calculate the radionuclide concentration on vegetation due to direct contamination and the concentration of radionuclide in dry soil.

3.6. Ground Concentration

The ground concentration mainly depends on the ground deposition in the earlier section. It also depends on effective rate constant and duration of the discharge of the radioactive material. The ground concentration can be calculated by using the equation [5],

$$C_{gr} = \frac{d_i\left[1 - \exp\left(-\lambda_{E_i^s} t_b\right)\right]}{\lambda_{E_i^s}} \quad (11)$$

where d_i is the total ground deposition rate (Bq·m^{-2}·d^{-1}); $\lambda_{E_i^s}$ is the effective rate constant for reduction of the activity in top 10 to 20 cm of soil (d^{-1}); there $\lambda_{E_i^s}$ = $\lambda_i + \lambda_s$, λ_s is the rate constant for reduction of soil activity owing to processes other than radioactive decay; and t_b is the duration of the discharger of radioactive material (d).

3.7. Concentrations in Vegetation

Radionuclides intercepted by and retained on vegetation may result from fallout, washout, and irrigation with contaminated water or deposition of resuspended matter. External deposits can be taken up by foliar absorption into plants. Radionuclides may also be incorporated by uptake from the soil through roots, followed by internal redistribution of radionuclides within the plant. Processes that may lead to the reduction of radionuclide concentrations in vegetation include radioactive decay, growth dilution, wash-off of externally deposited radionuclides, leaching and soil fixation. Further removal of radioactive material from vegetation may occur due to grazing, harvesting, etc.

For conditions of prolonged deposition, such as from discharges, the following equation may be used to estimate the concentration $C_{v,i,1}$ due to direct contamination of nuclide I in and on vegetation,

$$C_{v,i,1} = \frac{d_i \alpha\left[1 - \exp\left(-\lambda_{E_i^v} t_e\right)\right]}{\lambda_{E_i^v}} \quad (12)$$

where $C_{v,i,1}$ is measured in Bq/kg dry matter for vegeta-

tion consumed by grazing animals and in Bq/kg fresh matter for vegetation consumed by humans; d_i is the deposition rate (from wet and dry processes) of radionuclide *i* on to the ground ($Bq \cdot m^{-2} \cdot d^{-1}$); α is the fraction of deposited activity intercepted by the edible portion of vegetation per unit mass (or mass interception factor, m^2/kg) as the results of both wet and dry deposition processes; for pasture forage the unit of mass is conventionally given in terms of dry weight, and for fresh vegetables the unit is in wet weight; $\lambda_{E_i^v}$ is the effective rate constant for reduction of the activity concentration of radionuclide *i* from crops (d^{-1}); where $\lambda_{E_i^v} = \lambda_i + \lambda_w$; t_e is the time period during which the crops are exposed to contamination during the growing season (d) (assumed to be 1 day); λ_w is the rate constant for reduction of the concentration of material deposited on the plant surfaces owing to processes other than radioactive decay (d^{-1}); and λ_i is the rate constant for radioactive decay of radionuclide *i* (d^{-1}).

3.8. Concentration for Uptake from Soil and Soil Adhering

The radionuclide concentration in vegetable arising from indirect processes *i.e.* uptake from the soil and from soil adhering to the vegetation is given by following equation as,

$$C_{v,i,2} = F_v \times C_{s,i} \tag{13}$$

where $C_{v,i,2}$ is measured in Bq/kg dry matter for vegetation consumed by grazing animals and in q/kg fresh matter for vegetation consumed by humans; F_v is the concentration factor for uptake if the radionuclide from soil by edible parts of crops (Bq/kg plant tissue per Bq/kg dry soil), it is conservatively assumed that all activity removed from the atmosphere becomes available for uptake from the soil; in addition, the selected values also implicitly take account of the adhesion of soil to the vegetation; and $C_{i,s}$ is the concentration of radionuclide *i* in dry soil (Bq/kg.), which can be defined as ,

$$C_{s,i} = \frac{d_i\left[1 - \exp\left(-\lambda_{E_i^s} t_b\right)\right]}{\rho \lambda_{E_i^s}} \tag{14}$$

where $\lambda_{E_i^s}$ is the effective rate constant for reduction of the activity concentration in the root zone of soil (d^{-1}), where $\lambda_{E_i^s} = \lambda_i + \lambda_s$; λ_s is the rate constant for reduction of the concentration of material deposited in the root zone of soil owing to processes other than radioactive decay (d^{-1}); t_b is the duration of the discharge of radioactive material (d) (assumed to be 1 day); and ρ is a standardized surface density for the effective root zone in soil (kg/m^2, dry soil) which is 260 [3].

The above equation refers to the total deposition and neglects the amount, which is adsorbed to the vegetation.

3.9. Total Concentration in Vegetation

The total concentration of the radionuclide on the vegetation at the time of consumption is

$$C_{v,i} = \left(C_{v,i,1} + C_{v,i,2}\right)\exp\left(-\lambda_i t_h\right) \tag{15}$$

where $C_{v,i}$ is measured in Bq/kg dry matter for vegetation consumed by grazing animals and in Bq/kg fresh matter for vegetation consumed by human; λ_i is the rate constant for radioactive decay of radionuclide *I* (d^{-1}); and t_h is a decay (hold-up) time that represents the time interval between harvest and consumption of the food (d) which is equal to 14 d.

3.10. Concentrations in Animal Feed

The transfer of radionuclide to animals will depend on the intake of the animal and the metabolism of the various radionuclides by the animal. The intake of radionuclides by animals depends on animal species, mass, age and growth rate of the animal, the digestibility of feed and, in the case of lactating animals, the milk is considered. For generic calculations, grazing animals' are assumed to be cattle, which during the grazing season, are on a diet of fresh pasture only. The grazing season depends on latitude and ranges from a few months to the whole year. The concentration of radionuclide *i* in animal feed is calculated by [5],

$$C_{a,i} = f_p C_{v,i} + \left(1 - f\right) C_{p,i} \tag{16}$$

where $C_{a,i}$ is the concentration of radionuclide *i* in the animal feed (Bq/kg dry matter); $C_{v,i}$ is the concentration of radionuclide i for pasture, calculated using Equation (15) with $t_h = 0$ (Bq/kg, dry matter); $C_{p,i}$ is the concentration of radionuclide in stored feeds (Bq/kg, dry weight), calculated using Equations (11)-(14) and substituting $C_{p,i}$ for $C_{v,i}$ with $t_h = 90$ days; and f_p is the fraction of the year that animals consume fresh pasture vegetation (dimensionless) which is 0.7 [3].

3.11. Concentration in Milk

The concentration of a radionuclide in milk is assumed to depend directly upon the amount and concentration level in the feed consumed by the lactating animal. The concentration of radionuclide *i* in milk can be estimated by using the equation [5],

$$C_{m,i} = F_m\left(C_{a,i} Q_m + C_w Q_w\right)\exp\left(-\lambda_i t_m\right) \tag{17}$$

where $C_{m,i}$ is the concentration in milk of radionuclide *i* (Bq/L); F_m is the fraction of the animal's daily intake

of the radionuclide that each liter of milk at equilibrium which is 0.01 d/L for I [5]; $C_{a,i}$ is the concentration of radionuclide i in the animal feel (Bq/kg, dry matter); $C_{w,i}$ is the concentration of radionuclide i in water (Bq/kg); Q_m is the amount of feed (in dry matter) consumed by the animal per day which is 16 kg, (dry weight) [3]; Q_w is the amount of water consumed by the animal per day, which is 0.06 (m^3/d) [5]; λ_i is the rate constant for radioactive decay of radionuclide i (d^{-1}), and t_m is the average time between collection and human consumption (assumed to be one day for fresh milk).

3.12. Concentration in Meat

The radionuclide concentration in meat also depends directly on the amount and contamination level of the feed consumed by the animal. The radionuclide concentration in meat is calculated in the same way concentration in milk. The same constraints exist except the default values. It can be calculated by using the following equation [5],

$$C_{f,i} = F_f\left(C_{a,i}Q_f + C_{w,i}Q_w\right)\exp\left(-\lambda_i t_f\right) \qquad (18)$$

where $C_{f,i}$ is the concentration of radionuclide i in animal flesh (Bq/kg); F_f is the fraction of the animal's daily intake of a radionuclide that appears in each kg of at equilibrium or at the time of slaughter *i.e.* for I it is 0.05 d/kg which have been taken from elsewhere [5]; $C_{a,i}$ is the concentration of radionuclide i in the animal's feed (Bq/kg, dry matter); $C_{w,i}$ is the concentration of radionuclide i in water (Bq/m^3); Q_f is the amount of water consumed by the animal per day, which is 0.04 m^3/d [5], and t_f is the average time between slaughter and human consumption of meat which is 20 days [5].

4. Results and Discussion

A computational code has been developed, using MathCAD Professional Software to solve the mathematical expressions in order to calculate the concentration of each radionuclide of iodine. Source-term can be calculated using the first part and concentration in different environmental media can be calculated using the second part of the code. The input parameters were measured for the TRIGA Mark-II reactor site, at AERE, Savar, Dhaka. The radiological concentration was estimated in different foodstuff (vegetation, milk, and meat) due to accidental release of radioiodine (^{131}I, ^{132}I, ^{133}I, ^{134}I, and ^{135}I) through the stack of the 3 MW TRIGA Mark-II research reactor. The results of the measurements are given in the following segments.

4.1. Maximum Air Concentration for Various Directions

Air concentrations were calculated with respect to the distance in 16 cardinal directions using the release rate mentioned above and with the help of Equation (7). **Figures 1-5** show calculated air concentration as function of distance for ^{131}I, ^{132}I, ^{133}I, ^{134}I, and ^{135}I respectively. The maximum air concentrations for all directions were found at 110 m distance from the core of the reactor and it was found to be highest in the southern (S) direction.

The values of the concentration along N, NE, E, SE, SW, W and NW directions are closer to that of S-direction. In radiation protection point of view, radiological doses were assessed in different environmental pathways such as ground deposition, immersion, inhalation and ingestion of vegetable, milk and meat considering the maximum concentration for all the directions.

4.2. Ground Concentration

Through dry and wet deposition, air borne particulates normally deposit on the ground surface which are the key factors for the increase of radionuclide in ground. Activity concentrations of radioiodine in ground were calculated using Equation (11), measured ground concentration of

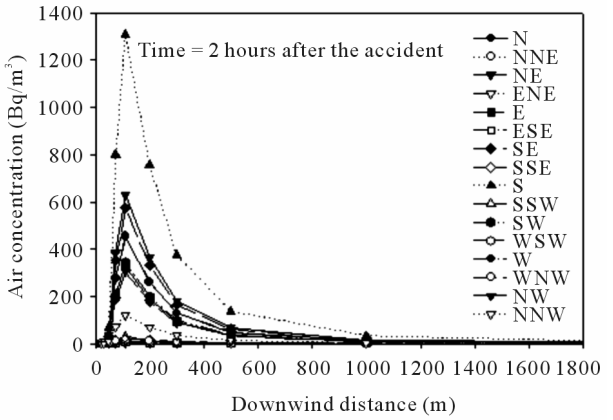

Figure 1. Air concentration as a function of downwind distance for ^{131}I.

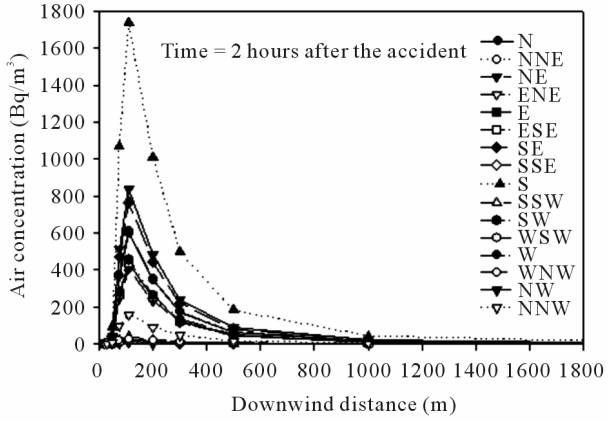

Figure 2. Air concentration as a function of downwind distance for ^{132}I.

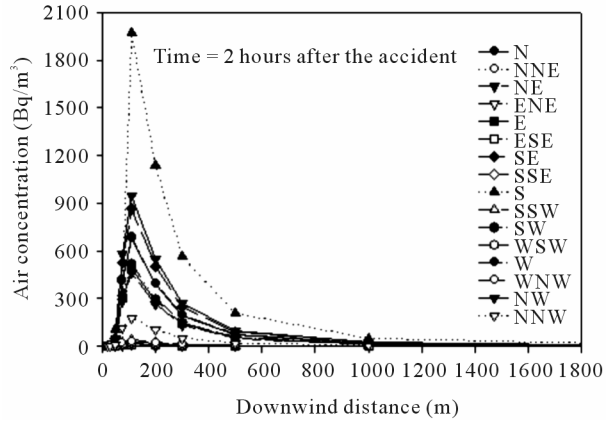

Figure 3. Air concentration as a function of downwind distance for ^{133}I.

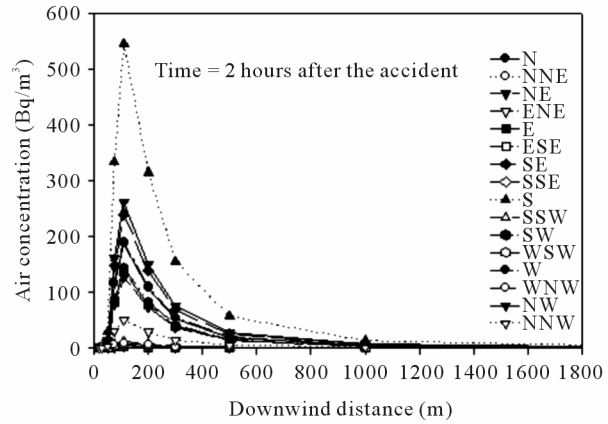

Figure 4. Air concentration as a function of downwind distance for ^{134}I.

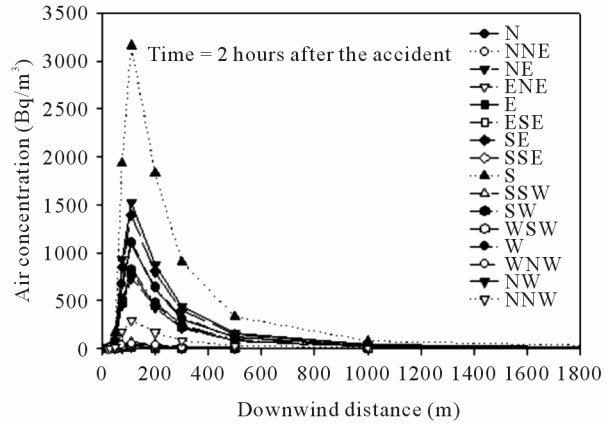

Figure 5. Air concentration as a function of downwind distance for ^{135}I.

^{131}I, ^{132}I, ^{133}I, ^{134}I and ^{135}I and total concentration (^{131}I + ^{132}I + ^{133}I + ^{134}I + ^{135}I) are graphically illustrated in **Figure 6** for eight (8) cardinal directions. The maximum ground concentration occurred immediately just after the accident in different directions which has been shown in **Table 2**. Maximum ground concentration was found in S-direction. With increasing time, the concentrations are found to decrease exponentially after the accident due to radioactive decay. This radionuclide is transferred to plants and then to meat and milk via ingestion and will be exposed to human directly and indirectly.

5. Concentration in Different Pathways

5.1. Ground Concentration

The activity concentration in vegetation occurs due to direct deposition of air borne radionuclides on the edible portion of the vegetables and uptake from soil. The concentration in vegetation for ^{131}I, ^{132}I, ^{133}I, ^{134}I, ^{135}I and total are shown in **Table 3** and plotted as a function of time for 8 directions, shown in **Figure 7**. This Table predicts that the concentration of vegetation due to ^{132}I, and ^{134}I is found to be zero which is due to very short half-life and ^{131}I is the dominant contributor of concentration in vegetation for long half life. **Figure 7** predicts that the concentration in vegetation decreased exponentially with time after the accident and within 60 days most of the activity disappeared and the Sequence of concentration of iodine is $C_{veg}{}^{131}\text{I} > C_{veg}{}^{133}\text{I} > C_{veg}{}^{135}\text{I}$.

5.2. Concentration in Milk

The radionuclide in milk arises due to consumption of contaminated feed by the lactating animal and its concentration in milk depends directly on radioactivity concentration of the feed consumed by the lactating animal. Concentrations of ^{131}I, ^{132}I, ^{133}I, ^{134}I, ^{135}I and total (^{131}I + ^{132}I + ^{133}I + ^{134}I + ^{135}I) in milk as a function of time for different directions are shown in **Figure 8** and the concentration in milk at time $t = 0$ is given in **Table 4**.

From the graph it is clear that the maximum concentration occurs at time $t = 0$ for each direction and is decreasing exponentially with time and become nearly to zero within 100 days. The **Table 4** shows that the maximum concentration was found in S-direction among all other directions. It was found the sequence of concentration as $C_{milk}{}^{133}\text{I} > C_{milk}{}^{131}\text{I} > C_{milk}{}^{132}\text{I} > C_{milk}{}^{135}\text{I} > C_{milk}{}^{134}\text{I}$, where "$C_{milk}$I" refers to the concentration of different isotopes of iodine in milk. The concentration of ^{133}I in milk is higher than all other isotopes of iodine because of its higher concentration in animal's feed.

5.3. Concentration in Meat

The radionuclide concentration in meat occurs via consumption of contaminated food—in the same way as concentration in milk. **Table 5** shows the concentration in meat immediately just after the accident for eight dominant directions. Maximum concentration was found again in S-direction and the sequence of the concentration of

Table 2. Maximum ground concentration for different directions at time $t = 0$ (*i.e.* just after the accident).

Direction	Ground concentration (Bq/m^2)					
	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	Total
N	4.301×E+5	8.284E+4	4.652E+5	9.856E+3	6.831E+4	1.056E+6
NE	2.919E+5	5.622E+4	3.157E+5	6.69E+3	4.637E+4	7.168E+5
E	3.106E+5	5.986E+4	3.359E+5	7.129E+3	4.941E+4	7.629E+5
SE	5.493E+5	1.059E+5	5.942E+5	1.262E+4	8.745E+4	1.349E+6
S	1.251E+6	2.411E+5	1.353E+6	2.872E+4	1.99E+5	3.072E+6
SW	3.285E+5	6.331E+4	3.553E+5	7.539E+3	5.226E+4	8.07E+5
W	4.359E+5	8.398E+4	4.715E+5	9.995E+3	6.928E+4	1.071E+6
NW	6.013E+5	1.158E+5	6.503E+5	1.379E+4	9.555E+4	1.477E+6

Table 3. Maximum concentration in vegetation for different directions at time $t = 0$ (*i.e.* just after the accident).

Direction	Concentration in vegetation (Bq/kg)					
	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	Total
N	3.764E+4	0	1.869	0	9.622E−12	3.764E+4
NE	2.554E+4	0	1.268	0	6.531E−12	2.554E+4
E	2.718E+4	0	1.35	0	6.96E−12	2.718E+4
SE	4.807E+4	0	2.387	0	1.232E−11	4.807E+4
S	1.094E+5	0	5.435	0	2.804E−11	1.095E+5
SW	2.875E+4	0	1.428	0	7.361E−12	2.875E+4
W	3.815E+4	0	1.894	0	9.758E−12	3.815E+4
NW	5.262E+4	0	2.612	0	1.346E−11	5.262E+4

Table 4. Concentration in milk for different directions at time $t = 0$ (*i.e.* just after the accident).

Direction	Concentration in milk (Bq/L)					
	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	Total
N	2.814E+4	5.511E+3	3.056E+4	656.123	4.515E+3	6.938E+4
NE	2.04E+4	3.996E+3	2.216E+4	475.711	3.274E+3	5.03E+4
E	1.454E+4	2.848E+3	1.579E+4	339.297	2.335E+3	3.585E+4
SE	2.571E+4	5.038E+3	2.792E+4	600.501	4.132E+3	6.34E+4
S	5.854E+4	1.147E+4	6.357E+4	1.367E+3	9.406E+3	1.444E+5
SW	1.538E+4	3.012E+3	1.67E+4	358.837	2.469E+3	3.792E+4
W	2.04E+4	3.996E+3	2.216E+4	475.711	3.274E+3	5.03E+4
NW	2.814E+4	5.511E+3	3.056E+4	656.123	4.515E+3	6.938E+4

Table 5. Concentration in meat for different directions at time $t = 0$ (*i.e.* just after the accident).

Direction	Concentration in meat (Bq/kg)					
	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	Total
N	7.549E+4	1.476E+4	8.196E+4	1.752E+3	1.21E+4	1.861E+5
NE	5.123E+4	1.002E+4	5.562E+4	1.189E+3	8.212E+3	1.263E+5
E	5.451E+4	1.066E+4	5.919E+4	1.267E+3	8.751E+3	1.344E+5
SE	9.641E+4	1.886E+4	1.047E+5	2.242E+3	1.549E+4	2.377E+5
S	2.195E+5	4.294E+4	2.384E+5	5.104E+3	3.525E+4	5.412E+5
SW	5.766E+4	1.128E+4	6.261E+4	1.34E+3	9.255E+3	1.421E+5
W	7.651E+4	1.496E+4	8.307E+4	1.776E+3	1.227E+4	1.886E+5
NW	1.055E+5	2.063E+4	1.146E+5	2.45E+3	1.692E+4	2.601E+5

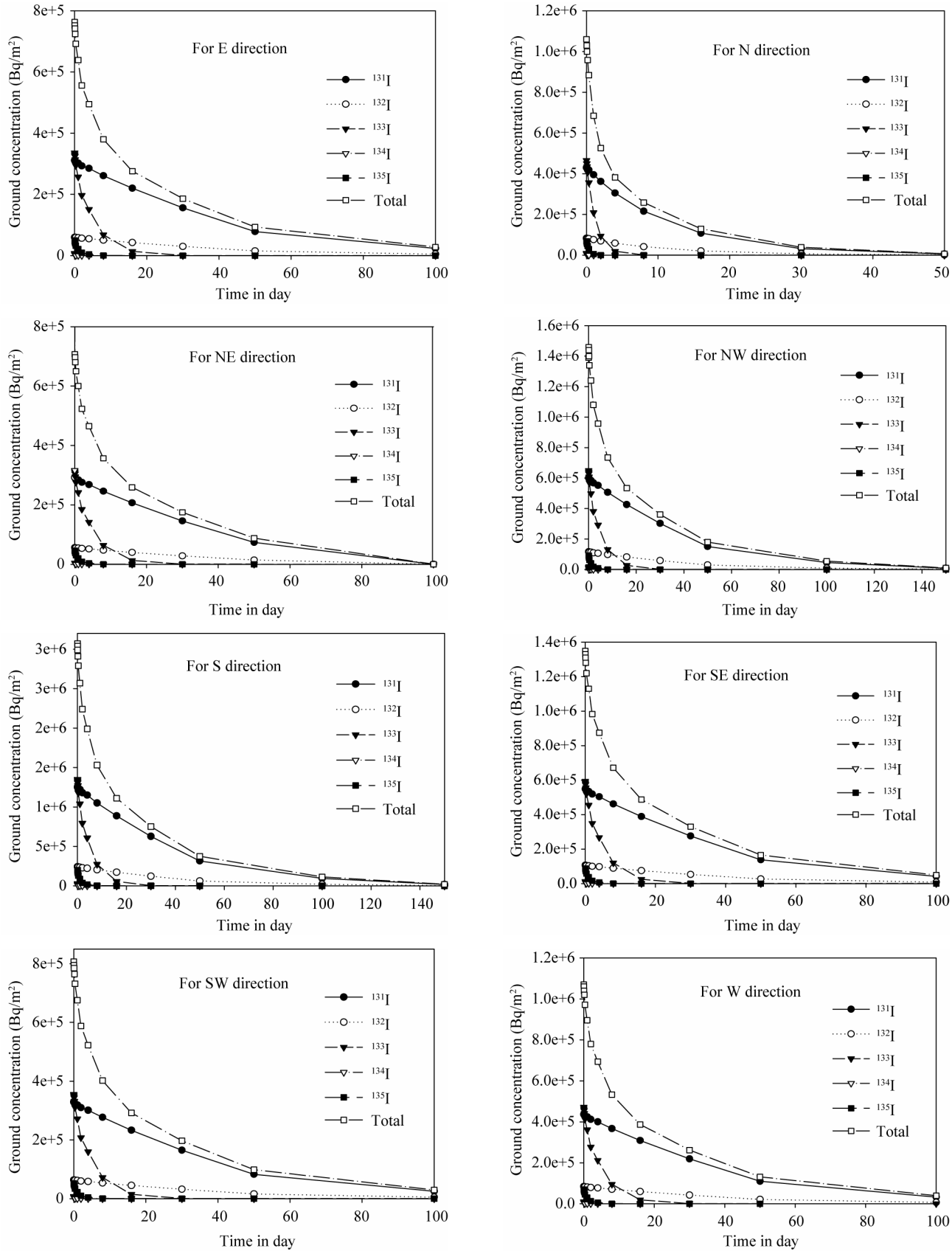

Figure 6. Ground concentration as a function of time for the directions of E, NE, NW, S, SE, SW, W and N.

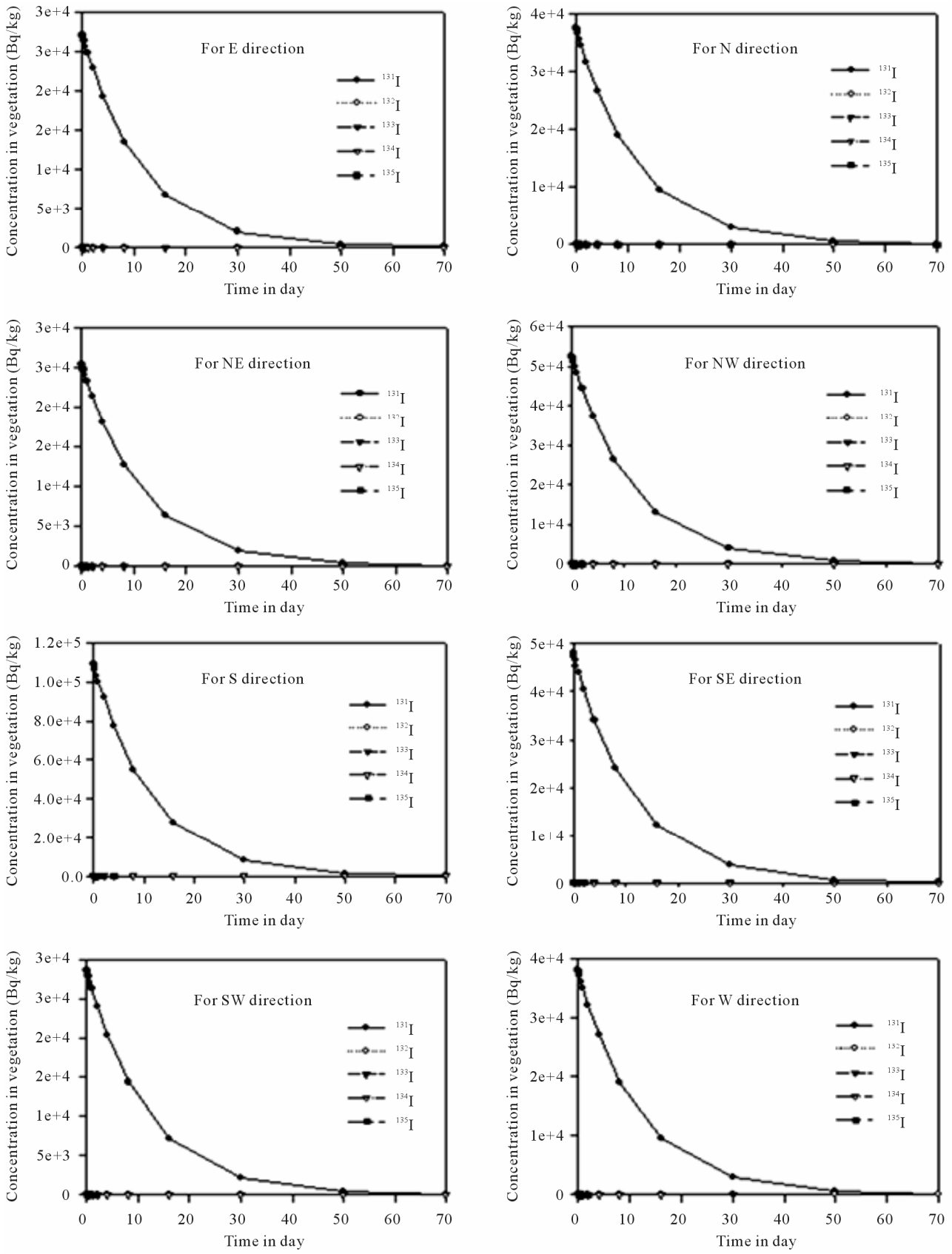

Figure 7. Concentration in vegetation (Bq/kg) as a function of time (day) for E, N, NW, SW, SE, NE, W and S.

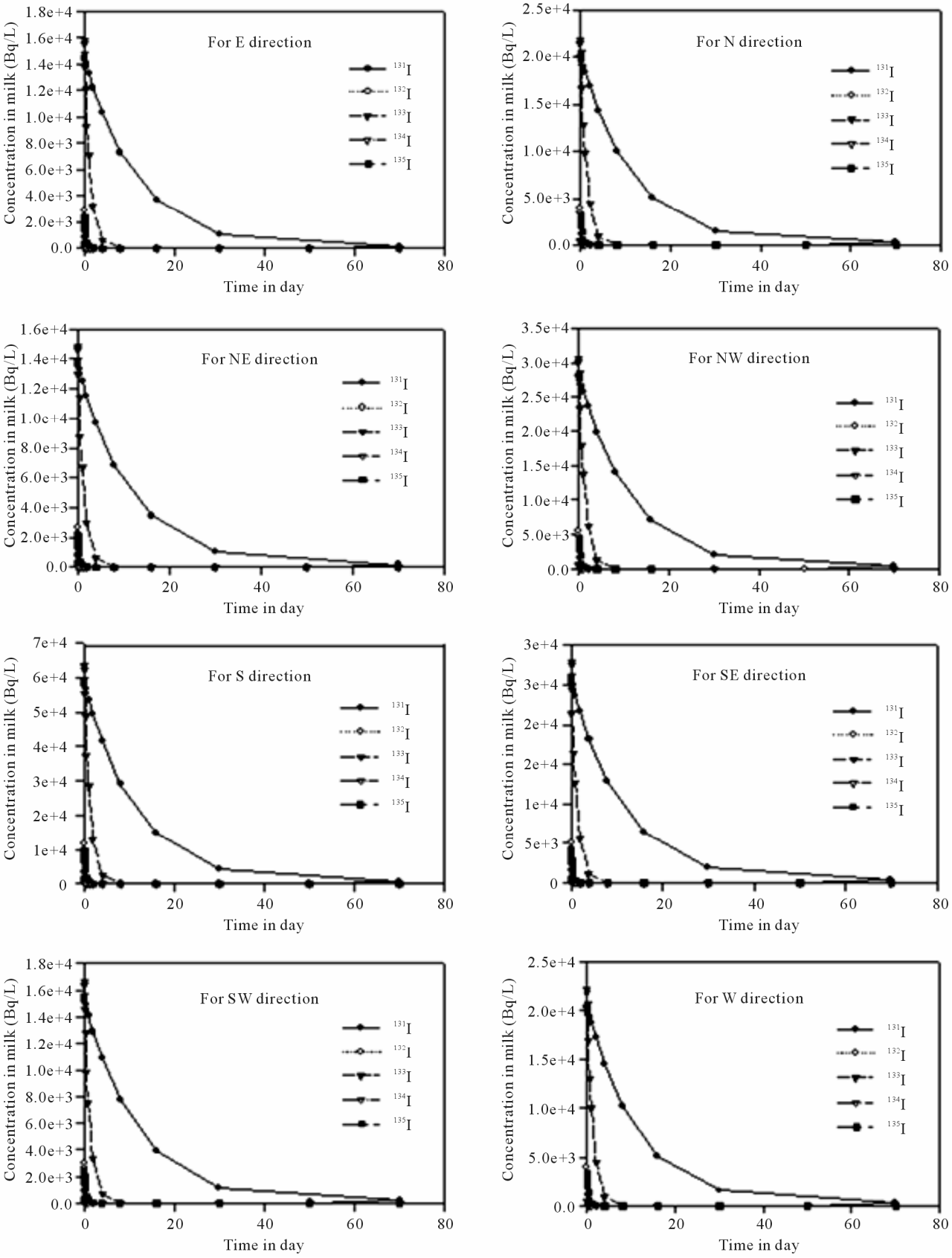

Figure 8. Concentration in milk (Bq/kg) as a function of time (day) for directions E, NE, NW, S, SE, SW, W and N.

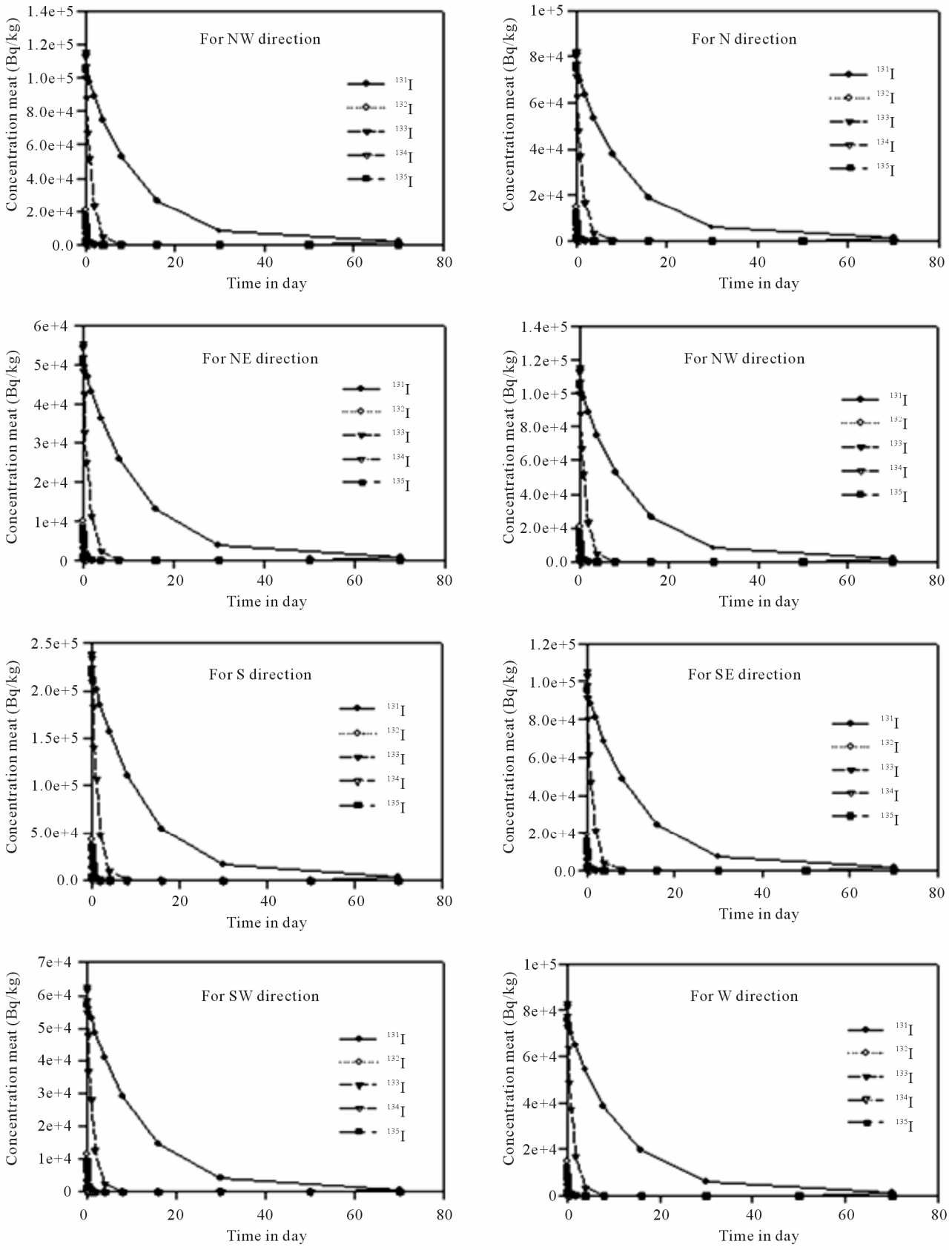

Figure 9. Concentration in meat as a function of time for the direction of E, SE, NE, W, NW, S and NE.

radioiodine is $C_{meat}{}^{133}I > C_{meat}{}^{131}I > C_{meat}{}^{132}I > C_{meat}{}^{135}I > C_{meat}{}^{134}I$ where "$C_{meat}I$" refers to the concentration of different isotopes of iodine in meat. The time dependent concentration of meat due to ^{131}I, ^{132}I, ^{133}I, ^{134}I, ^{135}I and total ($^{131}I + {}^{132}I + {}^{133}I + {}^{134}I + {}^{135}I$) in different directions were plotted and are shown in **Figure 9**. The concentration of ^{133}I is significantly higher than that of all other isotopes of iodine (*i.e.* ^{131}I, ^{132}I, ^{134}I, ^{135}I).

6. Concentration in Different Pathways

In this study, a computational code has been developed Based on the atmospheric dispersion phenomena for assessment of radiological concentration due to release of radioiodine for a hypothetical accident of the TRIGA Mark-II research reactor. Based on the assumed hypothetical accidental condition, activity of the radioiodine ^{131}I, ^{132}I, ^{133}I, ^{134}I and ^{135}I in the reactor core and their release rate were calculated. The air concentrations for these five isotopes of iodine in 16 directions were presently calculated with respect to downwind distance from the core of the reactor. The maximum air concentrations for all the 16 directions were found at 110 m distance from the reactor core. Maximum value of air concentration for all of the radioisotopes of iodine was found along S-direction and the lowest was found in NE direction. The ground concentration, concentration in vegetation, milk, and meat for the above-mentioned radioisotopes of iodine were measured for 8 directions (*i.e.* N, NE, E, SE, S, SW, W, and NW) as a function of time. The concentration in the different pathways of the radioisotopes of radioiodine are very low in other 8 directions (*i.e.* NNE, ENE, ESE, SSE, SSW, WSW, WNW, and NNW), because of lower frequency of the wind in these directions and hence the calculation of the concentrations along these directions were avoided in this work.

Concentration in vegetation for ^{131}I was found to be highest than all other isotopes and for ^{132}I and ^{134}I the values were predicted to be zero. Concentration in milk of ^{133}I was higher and that of ^{134}I was lower within all other isotopes of iodine. The concentration in meat of ^{133}I was found to be higher than other isotopes of iodine and that was lower for ^{134}I. There should be an awareness and caution about taking plants or vegetable grown at the site of accident. This study might provide a guideline on the radiological safety measures that has to be taken for radiation protection due to ingestion of vegetation, milk and meat from the reactor site at AERE in case of a radiological accident.

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