Atmospheric trajectory analysis of Cesium-137 from proposed nuclear power plant site in Bangka Island, Indonesia

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Abstract. Environmental risk assessment for nuclear power plant (NPP) operation is important to monitor the level of radionuclide concentration in the atmosphere and to determine the health risks associated with potential external radiation exposure. A NPP site was proposed in Bangka Island, Indonesia, 554 km from Johor Bahru, Malaysia. In the event of postulated nuclear emergency, the radionuclide dispersion from Bangka Island can possibly arrive in Malaysia's atmosphere due to its close distance with Malaysian border. The purpose of this study is to assess the trajectories of Cs-137 radionuclide towards Malaysia from Bangka Island NPP site. A simulation was conducted using Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) to describe the movement of radionuclides in the atmosphere from Bangka Island towards Malaysia. The result shows the trajectories and direction of both radionuclides are very much affected by the monsoon season, as well as the meteorological characteristics such as wind speed and direction. In the simulated event of radioactive release in 2019, the trajectories can be seen moving directly towards Malaysia in May, June, July, August, September and October. It is concluded that if Indonesia were to proceed with the NPP construction in Bangka Island, necessary preparation such as emergency plan and risks mitigation should be strategized early in Malaysia to safeguard the public and the environment.

1. Introduction

Radioactive contamination, commonly known as radiological contamination, is the deposition of radioactive substances on a surface or inside a space, where their existence is accidental or undesirable. Radioactive contamination in the environment depends on the characteristics of radioactive pollutant, the level of emissions or radiation exposure, and its pathways through the environment [1]. Radionuclides, whether natural or man-made are present in the environment and in human body. It travels through air, water and through the food chain, and at the same time emits radiation through radioactive decay process. Radioactive material movement in air is influenced by the weather. Climate behaviours such as air currents, wind speed, rain and snow highly influence the movements of radionuclide in air, which eventually effect the area and size of contaminated area from radionuclide distribution [2].

The Fukushima Daiichi nuclear accident in Japan has highlighted the importance of dispersion forecasting system to evaluate the movement of radioactive materials in air originated from nuclear facilities like nuclear power plants (NPP). The dispersion forecasting system should be established not only in the homeowner country, but also at the neighbouring countries with the purpose to evaluate possible risks and to provide detailed emergency plan for possible nuclear emergency events. An early analysis made by the authorities will provide extra measures and ample preparation to the affected countries to protect the public and the environment from unnecessary exposure during nuclear event.

In the Southeast Asia region, Indonesia is the only country that have consistently pursuing the plan to include nuclear power in its national energy mix. As part of the nuclear power infrastructure development plan, research and studies were conducted to identify possible risks and hazard originated from NPP construction operation in Indonesia. There are a number of proposed sites for NPP construction in Indonesia, and the closest location to Malaysia is the Sebagin site in Bangka Belitung province. The probabilistic risk assessments, especially the events related to radioactive release to the environment have been actively conducted by many researchers in Indonesia [3,4]. For example, a study by Pande Made Udiyani and Surip Widodo in 2012 entitled 'The Determination of Atmospheric Dispersion Coefficient for PWR Reactor Accident Analysis in Indonesia Site' was conducted to determine the value of the dispersion coefficient for the selected potential site in order to determine the values of accepted environmental doses for nuclear power plants in Indonesia [5]. Notwithstanding the fact that atmospheric dispersion risk assessments were actively conducted in Indonesia, the importance of risk assessments of radioactive dispersion in the areas beyond the international boundaries of the NPP location cannot be neglected.

This study is conducted to observe the movements of radioactive pollutants toward Malaysia from NPP site in Indonesia during nuclear accident scenario. This study serves as a cornerstone and a valuable source of reference and information for further study to be continued in order to ensure readiness to face nuclear fallout in Malaysia vicinity. The data obtained from this study can also be used and improvised by local authorities in order to plan for emergency procedures in the event of nuclear fallout in the unforeseen future.

2. Study Area

The trajectory observation area in this study is the NPP site in Bangka Island Indonesia as the source of origin, and Malaysia as the affected area. Pulau Bangka is an island located on the east of Sumatera, with a population of approximately 1 million. It is the 9th largest island in Indonesia and the main part of the Bangka-Belitung province. The inverted S-shaped of Bangka Island is roughly 11340 km^2 which generally occupied by low, rounded hills about 50 meters above sea level and separated by broad and open valley [5]. Bangka Island is fairly far from the Indonesia-Malaysia border, and the nearest city is Johor Bahru, about 554 km of direct distance measurement.

3. Methodology

This study utilizes the atmospheric dispersion modelling to simulate the movement pattern of radioactive particles in atmosphere using Hybrid Single Particle Lagrangian Integrated Trajectory System (HYSPLIT) software. HYSPLIT is a computer model developed by the National Oceanic and Atmospheric Administration (NOAA) of USA to measure trajectories of air parcels and the concentration of air pollutants. The model calculation method is a combination between the Lagrangian technique and Eulerian paradigm, where a rotating reference frame for advection and diffusion measurements of air parcels trajectories from their original position, is combined with three-dimensional grid as a reference frame for measuring pollutant air concentrations [6]. Meteorological data input in HYSPLIT is 'NCEP/NCAR Reanalysis' database, extracted from open access global meteorological data provided by National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) of USA [6].

The trajectory simulation was run for a daily emission over a year with reference to meteorological data of 2019. To get a clear observation of atmospheric movement in extreme nuclear emission scenario, the emission input is set equivalent to the estimated release of Caesium during Fukushima accident in 2011 [7,8]. The emission height was set to 60 meters above ground level as the emission origin.

As additional analysis of the radiation impact, another simulation is conducted to find the concentration of radionuclide and the effective dose rate (EDR) in Johor Bahru. In the simulation, the

EDR due to radioactive releases was calculated from the concentration data. For EDR, Caesium (Cs-137) were chosen as the radioactive pollutant input. Cs-137 has long half-life of 30 years and emits gamma radiation. Since Cs-137 stays longer in the environment, it can travel a long distance across the globe. Long term exposure to Caesium can cause stochastic health effects such as cancer or tumour [9]. Table 1 shows the radionuclide input data in HYSPLIT.

Table 1. Radionuclides Input Data.

Properties	**^{137}Cs**
Phases	Particle
Half-life (days)	10,960
Annual release in normal operation (GBq)	9.4×10^{-1}
Emission rate from Fukushima accident (Bq hr^{-1})	1.0×10^{15}

4. Results and Discussion

The simulation for the radionuclide's trajectory pattern were done using HYSPLIT software. The trajectories were plotted in a regional map for 3 consecutive days to observe the direction and distance of radionuclide movement through the atmosphere. Figure 1 shows the trajectory pattern projected for each month in 2019. The blue, green and red lines indicate the trajectories for the first 3 days (72 hours). The dots on the trajectory lines represents the location and the heights of the observed particle every 24 hours from the emission origin. The dots are used as reference to estimate the time taken by the radioactive particles to travel across the international boundary after the initial release.

Since the emission point is set at 60 meter above the ground, which is slightly above the average height of the land above sea level in Bangka Island, the movement is generally not obstructed by higher topography or tall building in the area. This setting allows the particle movement to reach the furthest distance without consideration of possible obstruction along the dispersion pathways.

4.1 Trajectory Analysis

Generally, the particle movement follows the wind current on different level of altitudes. The wind current depends on the climate characteristics of certain climate seasons. Therefore, general movement of the radioactive particle can be estimated using historical wind data. This scenario is clearly depicted in Figure 1, where the direction of radioactive particles trajectories is different for each month. The radioactive particle is moving towards Malaysia from May to November, which is the period of Southwest Monsoon season according to Malaysian climate. During this period, majority of the wind direction blows toward the north, northeast and northwest of Bangka Island, where Malaysia is located [10]. It can be concluded that the Southeast Monsoon can be classified as a risk period of radioactive dispersion in Malaysia, where the radioactive particles are certainly moves toward Malaysia's atmosphere from Indonesia.

Even though the direction of particle movement can be predicted using seasonal climate characteristics, it is only applicable for general prediction for a very large area. For a smaller area and shorter period of time in the season, the wind direction is different every time and day. With reference on Figure 1, when the emission occurs on 1st January, the particle moves towards the southeast from the emission point. However, on 2nd January, the particle moves toward the east for about 24 hours, before changing direction towards the south on the second day, then towards southeast the 3 days after. This scenario shows that on smaller time scale, the wind direction is unpredictable, which may cause a distinct margin of error in the estimation of possible affected area using the average wind direction.

The graph under the trajectory map shows the movement of the particle in different altitude above the ground level. Depending on the wind current, precipitation process and the surface topography, the

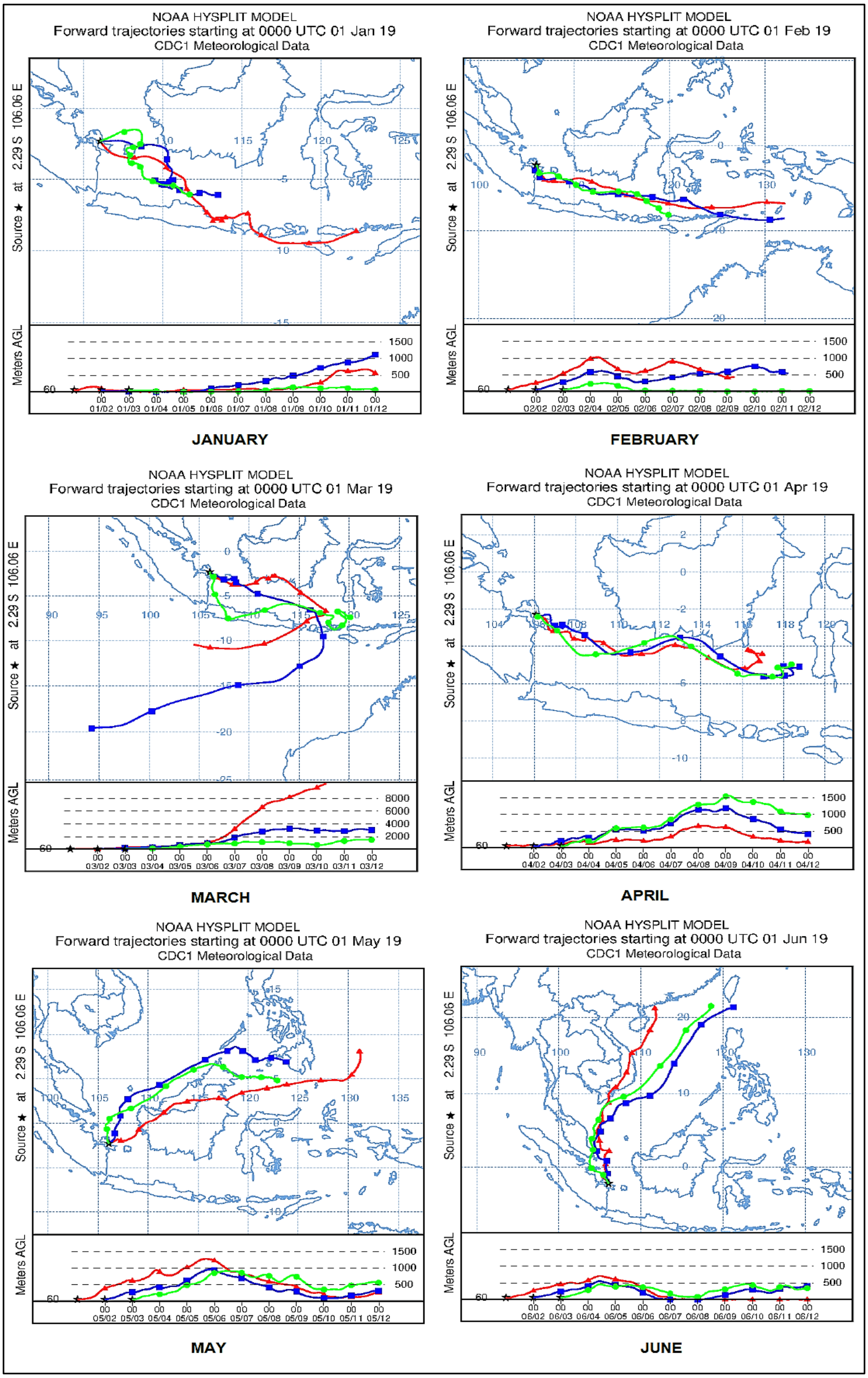

Figure 1. Monthly radionuclide forward trajectories (continue..)

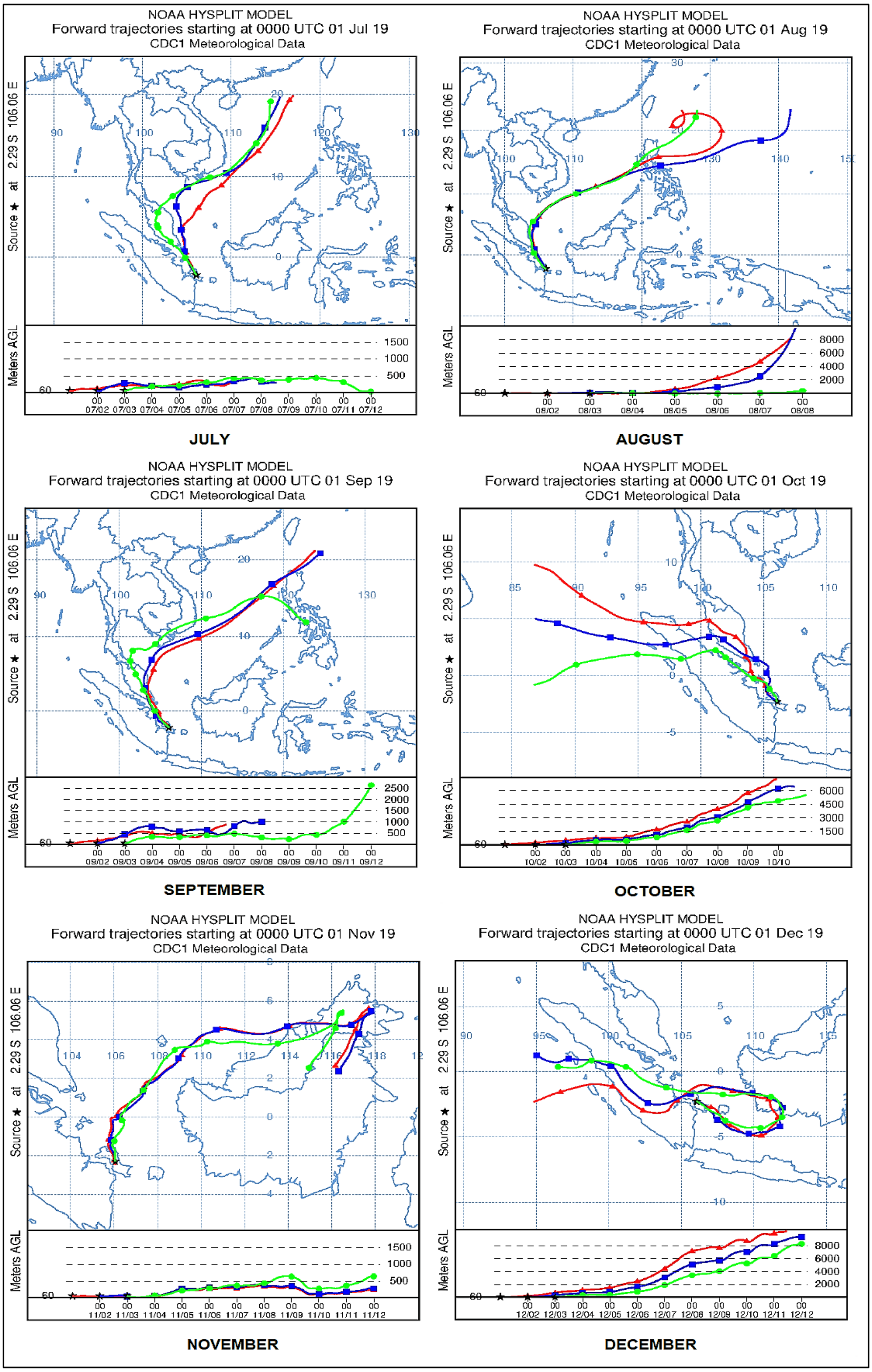

Figure 1. Monthly radionuclide forward trajectories

particles will move to higher or lower altitudes. From the graphs, particle movement above 1000 m altitude can travel farther in 24 hours compared to lower altitudes. This condition corresponds to general assumption that wind speed increase at higher altitudes when there are no significant obstacles [11]. This trajectory scenario shows that normal or accidental release from the NPP site in Bangka Island will arrive in Malaysian atmosphere any time and fully influenced by the meteorological factors. If the amount of emission is large, the risks will be significantly higher. However, the time and location of particle deposition from the atmosphere cannot be estimated from the graph. With only the wind speed and direction data, the distance and the location of particle deposition is not easily predictable. Additional climate data such as the seasonal and climate behaviour like precipitation, cyclone, wet and dry season is needed in the estimation of particle deposition from the atmospheric pathways.

The trajectory analysis is the simplest analysis to predict the movement of radioactive particle in air during nuclear emergency. It can be used as initial risk assessment right after the onset of a nuclear accident to predict the potential affected area from radionuclide dispersion in air. Emergency evacuation or sheltering order can be executed immediately, hence reducing the exposure time from the radionuclide deposition to the effected population. However, the analysis is not capable to estimate size of affected area and the health risks due to radioactive deposition or radiation exposure.

4.2 EDR data

The concentration data and external effective dose rate were obtained in the second simulation. A concentration reading point is set at Johor Bahru coordinate to determine the concentration of Cs-137 and to calculate the EDR in Johor Bahru area following 6 hours emission from NPP in Bangka Island. The EDR is calculated using Equation 1 below,

$$\mathrm{EDR\ (mSv/yr)} = \Sigma\mathrm{DCF}\ [(\mathrm{mSv/yr})/(\mathrm{kBq/m^3})] \times \mathrm{C}\ (\mathrm{kBq/m^3}) \times 0.2 \qquad (1)$$

where DCF is the dose conversion factor of the radionuclides [12], C is the activity concentrations of Cs-137 and 0.2 is the occupancy factor.

Table 2 shows the average monthly concentration of Cs-137 and the effective dose rate in Johor Bahru from normal operation scenario and hypothetical accident scenario. The concentration values are different each month because it is influenced by the meteorological characteristics in the dispersion pathways in the simulation. The highest average concentration for normal operation is in April 2019 with $3.35 \times 10^{-14}\ \mathrm{kBq/m^3}$, while for the hypothetical accident the highest concentration is in April with $0.31 \times 10^{2}\ \mathrm{kBq/m^3}$. During April and May is the period where the Southeast Monsoon is changing to Southwest Monsoon. During the monsoon change, higher amount of rainfall and unstable wind behaviour will occur in Johor Bahru, which caused higher deposition and concentration of Cs-137 in the area.

During normal operation, the average effective dose rate of Cs-137 detected in Johor Bahru is very low due to the controlled emission in the NPP safety requirements. Malaysia Atomic Energy Licensing Board (AELB) guideline stated that for radiation safety assessment, the control limit for external radiation dose rate is 0.5 µSv per hour, and the annual effective dose limit for public is 1 mSv per year [13]. The dose value may not cause health risks to the population in Johor Bahru in a short term, but long period observation should be conducted to determine the probable stochastic effect from it.

Meanwhile, for the hypothetical nuclear accident, the effective dose is significantly higher, way above the 1 mSv annual limit for the public, with maximum reading of 397 mSv/yr in April. From the monthly data, the annual average dose is 1.53×10^{2} mSv for 2019. This value is obtained in a condition where a person is exposed to radiation without shielding and sheltering. Hence, the value did not represent the real total dose received by the person, but only represents the estimated maximum dose rate received from detected concentration in the atmosphere.

Table 2. Average Concentration and Average Effective dose of Cs-137

Month	Average Concentration (kBq/m^3)		Average Effective Dose Rate (mSv/yr)	
	Normal Operation	Hypothetical Accident	Normal Operation	Hypothetical Accident
January	1.35×10^{-14}	0.11×10^{2}	1.45×10^{-15}	1.73×10^{2}
February	2.05×10^{-14}	0.17×10^{2}	2.92×10^{-15}	1.27×10^{2}
March	1.90×10^{-14}	0.17×10^{2}	2.48×10^{-15}	1.54×10^{2}
April	3.35×10^{-14}	0.31×10^{2}	4.22×10^{-15}	3.97×10^{2}
May	3.15×10^{-14}	0.14×10^{2}	4.00×10^{-15}	1.08×10^{2}
June	8.50×10^{-15}	0.08×10^{2}	1.17×10^{-15}	1.24×10^{2}
July	8.50×10^{-15}	0.08×10^{2}	1.32×10^{-15}	1.13×10^{2}
August	6.00×10^{-15}	0.06×10^{2}	9.87×10^{-16}	5.25×10^{1}
September	1.35×10^{-14}	0.11×10^{2}	2.27×10^{-15}	1.26×10^{2}
October	2.85×10^{-14}	0.13×10^{2}	2.83×10^{-15}	7.39×10^{1}
November	3.05×10^{-14}	0.29×10^{2}	2.68×10^{-15}	1.64×10^{2}
December	1.30×10^{-14}	0.13×10^{2}	1.44×10^{-15}	2.21×10^{2}

The EDR calculated in this study is not enough to estimate the absorbed and effective dose for Malaysia. The data obtained is only a simple prediction dose for Johor Bahru, which cannot represent the dose for Malaysia all together. Further analysis is needed to estimate the dose received by the public in different scenario and to predict the possible health effect from the exposure of radiation. Long term effects to the environment should be included in the analysis to establish a full-scale risk assessment for Malaysia from the postulated nuclear accident in Indonesia.

5. Conclusion

From the simulation, it is concluded that dispersion from NPP site on Bangka Island can reach Malaysia as early as 2 days during nuclear emergency equivalent to Fukushima accident in 2011. The Malaysian government should establish an emergency plan for nuclear accident scenario as a preparation to protect the public from unnecessary exposure in such scenario. Collaborative studies should be conducted with Indonesia to identify the potential risks of atmospheric dispersion from Indonesia to Malaysia.

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