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Radiological Impact Assessment of Fukushima Daiichi Nuclear Accident on Malaysian Marine biotas via Ocean Partway using Erica Code System

(Penilaian Kesan Radiologi terhadap Kehidupan Akuatik melalui Lautan Pasifik ke Malaysia Akibat Bencana Nuklear Fukushima Daiichi dengan Kod-Sistem Erica)

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ABSTRACT

Fukushima Daiichi nuclear disaster led to radioactive contamination crisis was resulted from a series of system failures, nuclear meltdown and radioactive material releases, following the 9.0 magnitude of earthquake and tsunami on March 11, 2011. The objectives of this study were; to investigate the movement of radionuclides based on oceanography and morphology of Pacific Ocean and Southeast Asia (Malaysia); to estimate the time for radionuclides to reach Malaysia and to calculate the amount of total absorbed dose rate for selected marine biotas namely benthic fish and pelagic fish. ERICA code system was used because it has the ERICA integrated approach to assess the radiation risk of biota. The estimations of radionuclide discharge from Fukushima Daiichi nuclear disaster were based on Cs-137 (half-life of 30.17 years), I-131 (half-life of 0.02 years). The parameters such as discharge rate of radionuclides (Bq/s), water depth (m), the distance between the target coast of Malaysia and radionuclide release point (m), the distance between the receptor and radionuclide release (m) and the velocity of the water/ocean currents (m/s) were studied. The results showed that the minimum estimated arrival time of radionuclides to reach Malaysia is located in Sandakan, Sabah, which is approximated at 4.82 years (Dec 2015) with an average of 5.039±0.310 years after the accident. Meanwhile, maximum estimated arrival time of radionuclides to Malacca is 5.87 years (Jan 2017) with an average of 5.527±0.480 years. The lowest estimated total absorbed dose rate by benthic fish is 0.0583 μGy/h with an average of (6.33±0.71) × 10^{-2} μGy/h in Malacca whereas the highest estimated total absorbed dose rate by benthic fish is 0.0751 μGy/h with an average of (7.11±0.57) × 10^{-2} μGy/h in Sandakan, Sabah. Pelagic fish in Malacca shows the lowest estimated total absorbed dose rate of 0.00149 μGy/h with an average of (1.62±0.18) × 10^{-3} μGy/h whereas Sandakan, Sabah showed the highest estimated total absorbed dose rate of 0.00193 μGy/h with an average of (1.83±0.15) × 10^{-3} μGy/h. The total absorbed dose rate and risk quotient of ERICA code system show that for all reference organisms, the probability of exceeding the selected screening dose rate of 400 μGy/h by aquatic biota is below the probability selected. Therefore, no measurable population of chronic exposure effects would occur at this stage. Nonetheless, a normal experimental analysis of fish samples should be performed in order to monitor the radiation effects to marine ecosystem.

Keywords: ERICA; Fukushima Daiichi nuclear disaster; marine biota; total absorbed dose rate

ABSTRAK

Kemalangan Loji Kuasa Reaktor Nuklear Fukushima Daiichi merupakan krisis pencemaran nuklear akibat kerosakan dan pelepasan bahan radiokatif akibat bencana gempa bumi bermagnitud 9.0 diikuti tsunami yang melanda Jepun pada 11 Mac 2011. Objektif kajian ini adalah; untuk mengkaji cara pergerakan radionuklid berdasarkan arus dan morfologi oseanografi Lautan Pasifik dan Asia Tenggara; menjangka masa pergerakan radionuklid ke Malaysia yang dibebaskan oleh kemalangan Reaktor Nuklear Fukushima Daiichi melalui perairan Malaysia dan mengira jumlah anggaran kadar dos terserap terhadap ikan bentik dan ikan pelagik. Kod sistem ERICA digunakan kerana ia mempunyai struktur berdasarkan Pendekatan ERICA Bersepadu untuk menilai risiko sinaran kepada biota. Radionuklid dianggap bebas daripada loji kuasa reaktor nuklear berdasarkan Cs-137 (separuh hayat 30.17 tahun) dan I-131 (separuh hayat 0.02 tahun). Parameter seperti kadar aktiviti radionuklid yang dibebaskan (Bq/s), kedalaman air (m), jarak antara sasaran pantai Malaysia dan tempat melepaskan radionuklid (m), jarak antara reseptor dengan tempat melepaskan radionuklid (m) dan kadar kelajuan air/arus pengairan lautan (m/s) telah dikaji. Hasil kajian menunjukkan jangkaan masa tercepat ketibaan radionuklid ke Malaysia adalah 4.82 tahun (Dis 2015) dengan purata 5.039±0.310 tahun bertempat di Sandakan, Sabah manakala jangkaan masa terlambat adalah 5.87 tahun (Jan 2017) bertempat di Melaka dengan purata 5.527±0.480 tahun. Jumlah anggaran kadar dos terendah terhadap ikan bentik mengikut jarak terjuah adalah 0.0583 μGy/j berpurata (6.33±0.71) × 10^{-2} μGy/j bertempat di Melaka manakala jumlah kadar dos tertinggi terhadap ikan bentik mengikut jarak terdekat adalah 0.0751 μGy/j berpurata (7.11±0.57) × 10^{-2} μGy/j di Sandakan. Ikan pelagik di Melaka mempunyai anggaran jumlah kadar dos terendah mengikut jarak terjuah iaitu 0.00149 μGy/j dengan purata (1.62±0.18) × 10^{-3} μGy/j manakala Sandakan mempunyai jumlah kadar dos tertinggi mengikut jarak terdekat iaitu 0.00193 μGy/j berpurata (1.83±0.15) × 10^{-3} μGy/j. Jumlah kadar dos terserap dan tahap risiko kod sistem

ERICA menunjukkan bahawa untuk semua rujukan organisma, kebarangkalian melebihi kadar dos terhad yang dipilih iaitu 400 µGy/j oleh biota akuatik adalah di bawah kebarangkalian yang dipilih. Oleh itu, tidak ada kesan pendedahan kronik kepada populasi yang dapat diukur pada peringkat ini. Walau bagaimanapun, penganalisian sampel ikan perlu dilakukan untuk memantau kesan sinaran terhadap ekosistem marin.

Kata kunci: Biota lautan; ERICA; jumlah kadar dos terserap; kemalangan Loji Kuasa Reaktor Nuklear Fukushima Daiichi

INTRODUCTION

The Fukushima Daiichi nuclear disaster triggered by the magnitude 9.0 earthquakes and associated tsunami on March 11, 2011 has led to a radioactive contamination crisis resulting from a series of system failures, nuclear meltdown and the release of radioactive material (UNSCEAR 2012). The estimated total activities of I-131 and Cs-137 released into the ocean were 1.2×10^{16} and 1.5×10^{17} Bq, respectively (IAEA 2011). Several studies have been conducted in Italy and Lithuania, regarding forecasting the behaviour and movement of Cs-137 and I-131 in the ocean pathways resulting from the Fukushima Daiichi nuclear accident (Laura et al. 2012; Lujaniene et al. 2011). According to the oceanography and Pacific Ocean current pathways, forecast of radionuclide released from Fukushima Daiichi Nuclear Power Plant will likely to reach Malaysia through Pacific Ocean pathways which may eventually give an impact to Malaysia marine biotas. As a matter of fact, the fisheries sector in Malaysia plays an important role in providing fish as a source of food and protein. In terms of biomass, the pelagic fish resource is the single most important fishery resource of Malaysia. The Exclusive Economic Zone of Sarawak contains the largest biomass of 879548 tonnes for Malaysia as a whole (Albert et al. 2003). Pelagic fish live in the pelagic zone of ocean or lake waters being neither close to the bottom nor near the shore in contrast with benthic fish, which do live on or near the bottom. The ERICA Tool is a software system that has a structure based upon the tiered ERICA Integrated Approach for assessing the radiological risk to terrestrial, freshwater and marine biotas (Brown et al. 2013, 2008). The objectives of this study were to investigate the movement of radionuclides based on oceanography and morphology of Pacific Ocean and Southeast Asia (Malaysia); to estimate the arrival time of radionuclides in Malaysia and to calculate the approximate amount of absorbed dose rate (µGy/h) by benthic and pelagic fish in Malaysia using the ERICA code system.

MATERIALS AND METHODS

Cs-137 and I-131 were selected as the radionuclides of interest for estimating the radiological impact of the Fukushima Daiichi nuclear accident on Malaysia marine biotas. Ten locations were selected as the receptor points namely Sandakan, Lahad Datu, Kudat, Kota Kinabalu in Sabah; Kuching, Bintulu from Sawarak; Kuala Terengganu, Kuantan, Malacca, Johor Bahru from Peninsula Malaysia (Figures 1 and 2). These receptor points were selected due to their strategic location for fishing activity and involve major ports in Malaysia. The parameters required to calculate the total absorbed dose rate were the discharge rate of radionuclides (Bqs^{-1}), the water depth (m), the distance between the target coast of Malaysia and radionuclide release point (m), the distance between the receptor and radionuclide release (m) and the velocity of the water/ocean currents (ms^{-1}).

In order to forecast the movement of radionuclide in the ocean, direction of wind and water current of Pacific Ocean have been studied. This information could be obtained from the literature and The National

Source: Google Map 2013

FIGURE 1. Selected receptor points for Sabah and Sarawak Malaysia

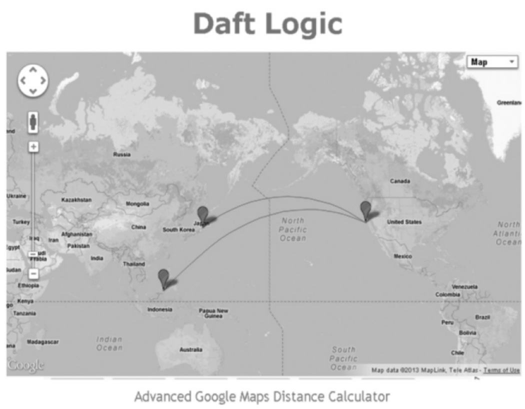
Source: Google Map 2013

FIGURE 2. Selected receptor points for Peninsula Malaysia

Oceanic and Atmospheric Administration (NOAA) of Pacific Ocean (NOAA 2012). NOAA has not only led national and international efforts to research, prevent and reduce the impacts of marine debris but also forecast the oceanography movement and behavior. Once the morphology and oceanography pathway of Pacific Ocean are well studied, the distance between the location of the accident site and receptor points could be estimated.

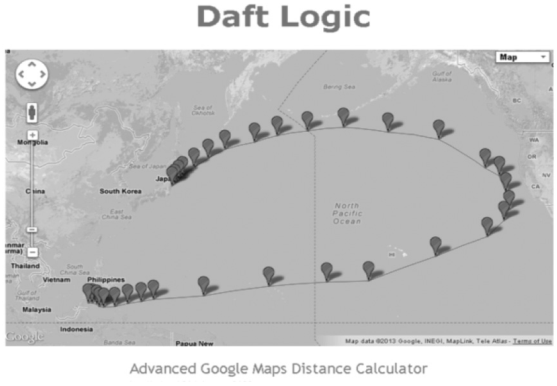
The distance between the release point and receptor point was calculated using the Advanced Google Maps Distance Calculator. Two sets of minimum and maximum output distances were performed using Daft Logic Vector Straight Lines and Daft Logic Distance Intermittent Lines in oder to obtain the standard deviation which shown in Figures 3 and 4.

The expected arrival time of radionuclides in Malaysia depends on two input parameters: the distance between the location of the accident site and receptor points and the Pacific Ocean current velocity. The average velocity of North Pacific currents is 0.13 ms^{-1} (Gregory & Michael 2001). Therefore, the arrival time



Source: Advanced

FIGURE 3. Minimum distances between release point and receptor point with Daft Logic Vector Straight Line



Source: Advanced Google Map Distance Calculator 2013

FIGURE 4. Maximum distances between release point and receptor Distance Intermittent Line point with Daft Logic

of radionuclides could be calculated by the following equation:

$$\frac{d}{v} = t, \tag{1}$$

where d is the distance between the accident site and receptor point following the radionuclide movement pattern (m), v is the average velocity of North Pacific currents (ms^{-1}) and t is the expected time of arrival of radionuclides in Malaysia (s).

An estimation of the absorbed dose rates by benthic and pelagic fish were calculated using the ERICA code system, which was integrate with the IAEA SRS-19 model. The following parameters were incorporated: Pacific Ocean depth, D (4028 m) (Knauss 1978); average Pacific Ocean current velocity, U (0.13 ms^{-1}) (Gregory & Michael 2001); distance between accident site and ten selected receptor locations, x (m); radionuclide discharge rate, Q_i (2.78×10^{11} Bqs^{-1} for Cs-137 and 2.78×10^{12} Bq^{-1} for I-131) (Chino et al. 2011). The concentration of radionuclides could be calculated using the following IAEA SRS-19 model equation:

$$C = \frac{962U^{0.17}Q_i}{D_x^{1.117}}\exp\left(-\frac{\lambda_i x}{U}\right), \tag{2}$$

where U is the average Pacific Ocean current velocity (ms^{-1}), D is the Pacific Ocean depth (m), Q_i is the discharge rate of radionuclide i (Bqs^{-1}), λ_i is the decay rate of radionuclide i (s^{-1}), x is the distance between the accident site and ten selected receptor locations (m) and c is radionuclide concentration in water (Bqm^{-3}). The total absorbed dose rate could be calculated with the radionuclide concentration obtained from the ERICA code system from (3) (Blaylock et al. 1993):

$$D_\gamma = 5.76 \times 10^{-4} E_\gamma n_\gamma \Phi C_0, \tag{3}$$

where D_γ is the γ-radiation dose rate (μGy/h), E_γ is the photon energy emitted during transition from a higher to a lower energy state (MeV), n_γ is the proportion of disintegrations producing a γ-ray, Φ is the absorbed fraction of energy E_γ (MeV) and C_0 is the concentration of the radionuclide in water (BqL^{-1}).

RESULTS AND DISCUSSION

The morphological and oceanography studies show that the movement pattern of radionuclides is expected to spread from the accident release site to the United States across the Pacific Ocean via the North Pacific current. Then, the radionuclides are expected to circulate back towards Southeast Asia (Malaysia) via the North Equatorial current, forming a circular pathway shown in Figure 5. This phenomenon is subjected to the driving force of wind. Wind is the primary driving force behind ocean surface water movement. These surface winds are responsible for

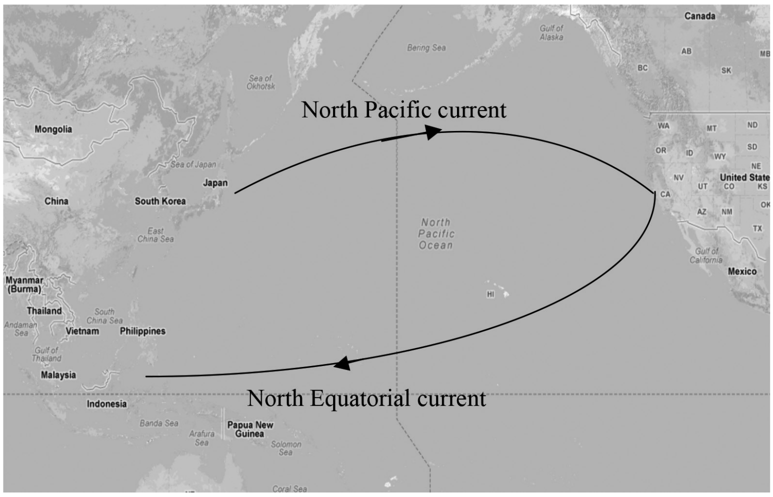
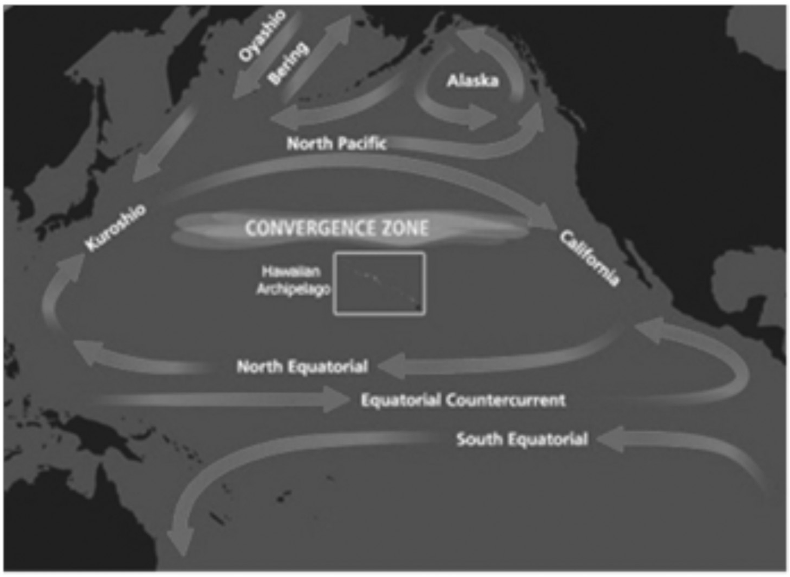


FIGURE 5. Expected movement patterns of radionuclides and distance from release point to receptor point according to morphology Pacific oceanography and ocean currents

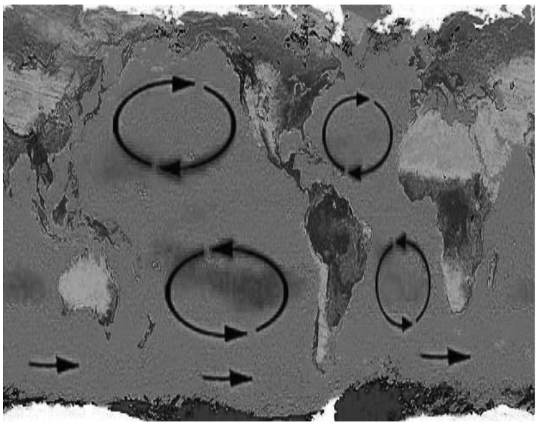
the major ocean currents and waves. The causes of the winds are almost completely due to the energy from the sun in the form of heat. The largest surface area subjected to surface winds is around the equator where the water is moved from east to west. As the water hits a continental mass, on the western side of the ocean, it piles up and flows right (north) in the northern hemisphere and left (south) in the southern hemisphere due to the Coriolis Effect (Figure 6). Warm tropical water is thus moved across the oceans from east to west and divided by the continents, where upon it flows toward the poles due to the Coriolis Effect and begins cooling. This creates the major surface ocean currents which are clockwise gyres in the northern hemisphere and counterclockwise in the southern hemisphere (Anderson 2003). The movement of the sea water is shown in Figure 7. The Advanced Google Maps Distance Calculator indicates minimum distance of 19775 km to Sandakan, Sabah, while the maximum distance of 24064 km is to Malacca as shown in Table 1.

The expected arrival time of radionuclides in Malaysia was calculated using (1), together with the results from the Advanced Google Maps Distance Calculator and the parameter of the North Pacific current velocity of $0.13\ ms^{-1}$. The expected arrival time of radionuclides in Malaysia is shown in Table 2. The minimum expected arrival time of radionuclides at Sandakan is 4.820 years after the time of the accident with an average of 5.039±0.310 years, whereas the maximum expected arrival time of



Source: Anderson 2003

FIGURE 6. Earth's surface ocean currents are caused by the winds, continental land mass obstruction and the Coriolis Effect



Source: NOAA 2012

FIGURE 7. Earth's surface ocean currents in Pacific Ocean

TABLE 1. Distance between accident site and receptor point

Receptor points	DLVSL*	DLDIL**
Sandakan	19775.188 km	21571.818 km
Lahad Datu	19818.723 km	21522.834 km
Kudat	19796.575 km	21850.928 km
Kota Kinabalu	19923.148 km	21984.960 km
Kuching	20705.636 km	22763.604 km
Bintulu	20380.891 km	22451.699 km
Kuala Terengganu	20946.344 km	23333.228 km
Kuantan	21059.432 km	23396.252 km
Johor Bahru	21225.890 km	23664.116 km
Malacca	21279.134 km	24063.735 km

* Daft Logic Vector Straight Line
**Daft Logic Distance intermittent line

TABLE 2. Expected arrival time of radionuclides to Malaysia

Receptor point	Minimum expected arrival time	Maximun expected arrival time	Average expected arrival time
Sandakan	4.820 years	5.258 years	5.039±0.310 years
Lahad Datu	4.834 years	5.246 years	5.040±0.291 years
Kudat	4.826 years	5.326 years	5.076±0.354 years
Kota Kinabalu	4.856 years	5.359 years	5.108±0.356 years
Kuching	5.047 years	5.549 years	5.298±0.355 years
Bintulu	4.968 years	5.473 years	5.221±0.357 years
Kuala Terengganu	5.106 years	5.688 years	5.397±0.412 years
Kuantan	5.133 years	5.703 years	5.418±0.403 years
Johor Bahru	5.174 years	5.768 years	5.471±0.420 years
Malacca	5.187 years	5.866 years	5.527±0.480 years

radionuclides at Malacca is 5.039 years with an average 5.527±0.480 years.

The total absorbed dose rate by benthic fish calculated by the ERICA code system with the IAEA SRS-19 model is shown in Table 3. The highest absorbed dose rate by benthic fish located in Sandakan is 0.0751 μGy/h with an average of $(7.11\pm0.57) \times 10^{-2}$ μGy/h, whereas the lowest absorbed dose rate located in Malacca is 0.0583 μGy/h with an average of $(6.33\pm0.71) \times 10^{-2}$ μGy/h.

The total absorbed dose rate by pelagic fish calculated by the ERICA code system with the IAEA SRS-19 model is shown in Table 4. The highest absorbed dose rate by pelagic fish located in Sandakan is 0.00193 μGy/h with an average of $(1.83\pm0.15) \times 10^{-3}$ μGy/h, whereas the lowest absorbed dose rate located in Malacca is 0.00149 μGy/h with an average of $(1.62\pm0.18) \times 10^{-3}$ μGy/h.

The result showed that the total absorbed dose rate to benthic fish is higher than pelagic fish. This may be

TABLE 3. Total absorbed dose rate to benthic fish

Receptor point	Lowest absorbed dose rate correspond to maximum distance µGy/h	Highest absorbed dose rate correspond to minimum distance µGy/h	Average absorbed dose rate µGy/h (×10^{-2})
Sandakan	0.0671	0.0751	7.11±0.57
Lahad Datu	0.0673	0.0749	7.11±0.54
Kudat	0.0660	0.0750	7.05±0.64
Kota Kinabalu	0.0655	0.0744	7.00±0.63
Kuching	0.0626	0.0708	6.67±0.58
Bintulu	0.0637	0.0722	6.80±0.60
Kuala Terengganu	0.0606	0.0697	6.52±0.64
Kuantan	0.0604	0.0692	6.48±0.62
Johor Bahru	0.0595	0.0685	6.40±0.64
Malacca	0.0583	0.0683	6.33±0.71

TABLE 4. Total absorbed dose rate to pelagic fish

Receptor point	Lowest absorbed dose rate correspond to maximum distance µGy/h	Highest absorbed dose rate correspond to minimum distance µGy/h	Average absorbed dose rate µGy/h (×10^{-3})
Sandakan	0.00172	0.00193	1.83±0.15
Lahad Datu	0.00173	0.00192	1.83±0.13
Kudat	0.00169	0.00192	1.81±0.16
Kota Kinabalu	0.00168	0.00191	1.80±0.16
Kuching	0.00161	0.00182	1.72±0.15
Bintulu	0.00164	0.00185	1.75±0.15
Kuala Terengganu	0.00156	0.00179	1.68±0.16
Kuantan	0.00155	0.00178	1.67±0.16
Johor Bahru	0.00153	0.00176	1.65±0.16
Malacca	0.00149	0.00175	1.62±0.18

resulted from the radionuclide being sedimented on the sea bed and directly expose to benthic fish. In general, the activity of radionuclide in the sediment is much higher than in the water and as a result, the dose rate from the sediment will be higher than the water (Blaylock et al. 1993).

Kryshev et al. (2012) estimated based on the data of radiation monitoring of the seawater by the Fukushima nuclear power plant showed that the highest dose rate range to fish from the coastal sea zone near Fukushima nuclear power plant on 30 March to 2 April 2011 was 167 - 333 µGy/h based on equilibrium 'concentration factor' approach. The dynamic ECOMOD model gave some lower dose rates of 38 – 50 µGy/h for this time period. For the later period 1 to 6 May, 2011, the 'concentration factor' model predicted decrease in fish exposure to 0.8 - 1.3 µGy/h, whereas the dynamic model calculated a much slower decrease to 16.6 - 20.8 µGy/h due to the biological retention of radionuclides (Kryshev et al. 2012).

In general occasion, the dose rates are much more lower compared to the nuclear accident. Studies show that the dose rate to marine biota in the Sellafield coastal area by Sazykina and Kryshev (2002) on the year 2001 was 9.08 × 10^{-3} µGy/h; dose rate to marine biota in the Cap de la Hague coastal area on the year 1997 was 8.75 × 10^{-4} µGy/h; dose rate to marine biota in the area impacted by Whitehaven phosphate plant on the year 1999 was 3.21 × 10^{-2} µGy/h. Apparently, our results showed that the dose rates were in the range and associated with their findings.

The results of dose rate are converted and compared to the activity concentration Bq/kg Index values relating to food ingestion limits set by Japan Department of Food Safety, Pharmaceutical and Food Safety Bureau, Ministry of Health, Labour and Welfare (MHLW). The conversion method and parameter proposed by Kryshev et al. (2012) were used. The prescribed safety limits for radioactive Cs-137 to fish is set to 500 Bq/kg (MHLW 2011). The results shown that the activity concentration after conversion are 151.3 Bq/kg for benthic fish and 3.9 Bq/kg which is far lower from the food ingestion limits.

IAEA (1992) and UNSCEAR (1996) suggested that the populations of freshwater and coastal organisms at chronic dose rate is below 400 µGy/h which indicates no measurable biological effects would occur. If the dose rate to aquatic organisms is less than the recommended level of 400 µGy/h, there should be no detrimental effects from radiation exposure at the population level and no quantifiable risk to the biota. If estimated dose rate exceed 100 µGy/h, then studies should be implemented to determine whether effects can be detected at the individual and population level for biota inhabiting the environment.

CONCLUSION

The results of the total dose rate and risk quotient of the ERICA code system show that for all reference organisms, the probability of the selected screening dose rate of 400 μGy/h for aquatic biota being exceeded is below the threshold selected; hence, no measurable effects of chronic exposure would occur at this stage (IAEA 1992; UNSCEAR 1996). This paper provides a simulation of dose assessment for marine biotas in Malaysia based on a closed system in which the current velocity and depth of the Pacific Ocean are constant. The arrival of radionuclides in Malaysia will follow the law of probability. Laboratory analysis of fish samples should be performed to calculate the total concentration of radionuclides in fish in order to assess the biological effects to the marine ecosystem of future exposure.

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