Radiological Impact Assessment of Class 3 Landfill of TENORM Waste from Tin Industry in Bangka Island

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ABSTRACT

This study assessed the potential radiological impact of a class 3 landfill as a disposal facility of the final tin slag from the tin industry in Bangka Island. Tin slag that contains TENORM (Technically Enhanced Naturally Occurring Radioactive Material) with activity concentrations above exemption level limits should be stored safely and securely. The radiological impact analysis of storing TENORM waste was carried out before and after the construction of a landfill facility. RESRAD OFFSITE version 3.2 software was used to simulate dose and cancer risk, and analyze the contribution of exposure pathways. Radionuclide concentration, landfill facility specifications, hydrogeological data, climatological data, and food and water consumption data were used as input parameters of RESRAD. The receptor was a resident farmer who lives 100 meters from the facility, grows his own food, and consumes water from his land. The total dose before and after the construction of the landfill were 3.13 mSv/year and 1.84×10^{-2} mSv/year while cancer risks were 5.69×10^{-3} and 6.50×10^{-5}, respectively. The exposure pathways from inhalation of radon become a major contributor to dose acceptance and cancer risk. Based on these results, the landfill facility is effective in reducing the potential impact of radiological hazards from dose acceptance and cancer risk.

1. INTRODUCTION

Bangka Island is a province in Indonesia which is famous for its tin industry (Sari, 2019). In 2010-2014 Indonesia was ranked the second-largest tin producer in the world with an average production of 89,900 tons (Brown et al., 2016). The activities of tin industry in Bangka Island have led to an increase in the concentration of radionuclides in the environment in the form of Technically Enhanced Naturally Occurring Radioactive Material (TENORM) which is found in tailings, slags, by-products, and by-product industry waste (Husain and Sakhnini, 2017). These wastes contain NORM, i.e., Ra-226 (Uranium series), Th-232 (Thorium series), and K-40 (Hamzah et al., 2018; Ibeanu et al., 2013). Based on the secondary data from Nuclear Energy Regulatory Agency of Indonesia (BAPETEN), the amount of tin slag that contains TENORM from tin industry in Bangka Island is approximately 43,800,000 kg (Iskandar et al., 2019). From the results of field observations, it was found that many people, including workers, store tailings and slag in their homes where the tailing and slag materials have potential radiological impacts on workers and residents, which can pose radiation exposure to them and contaminate the environment (Attallah et al., 2020).

RESRAD ONSITE version 6.5 has been used to estimate the potential radiological impact on workers in the fertilizer industry from phosphogypsum deposits containing TENORM (dos Reis and da Costa Lauria, 2014). The simulation results showed that the radionuclide Ra-226 and environmental exposure pathways from the ingestion of fish contributed to the high dose received by workers. Received doses that exceed the safe dose limit can increase a person's carcinogenic risk. In the provisions of the International Atomic Energy Agency (IAEA), when the concentration of a radioactive substance in TENORM is ≥1000 Bq/kg, then TENORM must be controlled as radioactive waste because it can contaminate the environment (International Atomic Energy Agency, 2003). In Nigeria, by-products from tin mining are dumped around the mining site. The waste

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contaminated the surrounding environment and caused exposure to the biosphere through the leaching process. Regulation regarding tailings waste management is needed to protect humans and the environment (Aliyu et al., 2015).

The safety assessment simulation of disposal for TENORM waste is very effective to reduce the radiological impacts on the residents and the environment (ALNabhani et al., 2016; Pontedeiro et al., 2007). In addition, the disposal which is engineered from soil materials can minimize costs and maintain waste integrity in the long term. The landfill method of TENORM waste from tin industry in Indonesia could be a disposal option. Based on The Regulation of Ministry of Environment and Forestry of The Republic of Indonesia, landfill facilities are divided into three classes, namely class 1, 2, and 3 (Ministry of Environment and Forestry, 2016). The difference between the three classes of landfill is the existence of the geomembrane. Class 1 consists of HDPE geomembrane double liners, class 2 consists of a single liner of HDPE geomembrane, and class 3 does not use HDPE geomembrane. The requirements and procedures for the landfill are contained in Regulation of The Ministry of Environment and Forestry of The Republic of Indonesia (Ministry of Environment and Forestry, 2016).

Bangka Regency was chosen as the research location because it is the main location for the tin industry in Indonesia. The safety assessment was conducted on the lowest class (class 3 landfill) to know whether this class provides enough safety at more affordable cost. So far, there has been no research discussing the use of class 3 landfills for TENORM waste from tin industry and its radiological impact on residents and the environment. Radiological impact estimation was assessed by using RESRAD OFFSITE version 3.2 software. The objective of the research is to assess the potential radiological impact to residents and the environment from the construction of a class 3 landfill facility for TENORM waste from tin industry in Bangka Island. The results of this study are expected as recommendation for tin stakeholders, for them to realize and eventually minimize the potential radiological impact.

2. METHODOLOGY

2.1 Study area

Most of the geological stratigraphy of Bangka Island consists of the Tanjung Genting Formation which consists of clay (Sari, 2019). Clay naturally has a good ability to prevent fluid flow which is very suitable to be used as a natural barrier to minimize the occurrence of radionuclide leakage (Carcione et al., 2019; Zhang, 2018). Therefore, the area with the Tanjung Genting Formation can be a potential area choice for the landfill facility. Based on previous studies, Bangka Regency was selected as a potential area for landfill which is marked with the red box (Figure 1) (Septiadi et al., 2018; Sucipta et al., 2020). The location that is close to the center of the tin industry makes transportation easier and saves time.

2.2 Concentration of radionuclides

Tin ore produced from the exploitation process is increased in tin content to 70% by the shaking table method or jig installation (Handini, 2020; Hutahaean and Yudoko, 2013). From this process, by-products will be produced such as monazite, ilmenite, and zircon which have high concentrations of radionuclides and are of economic value (Hamzah et al., 2018). In addition, the final tin slag which has a high concentration of radionuclides containing Ra-226, Th-232, and K-40 will also be produced but is no longer economically valuable. For this study, the final tin slag (as waste) was used as a source to be disposed in a landfill facility. The final tin slag contains Ra-226=6 Bq/g; Th-232=10.14 Bq/g; K-40=0.60 Bq/g (Iskandar et al., 2019).

2.3 Exposure scenario

In this study to estimate the dose and cancer risk of residents who spend time near the contamination zone, two exposure scenarios were used for the simulation, they are before and after the construction of a class 3 landfill facility. Class 3 landfill is the lowest class for contaminated solid waste. Class 3 consists of a compacted clay layer, primary leachate collection system (SPPL I), barrier soil, secondary leachate collection system (SPPL II), and protective layer. The requirements for each layer are contained in the Regulation of Ministry of Environment and Forestry of The Republic of Indonesia (Ministry of Environment and Forestry, 2016). Landfill facility has an exclusion zone with a radius of 100 meters, where within this distance is a limited activity. The exposure scenario assumes that primary contamination is transported to agricultural areas, wells, dwellings, and the groundwater flows from the NORM waste stack toward fishponds and livestock. Since they produce all their own food and consume water from the well near

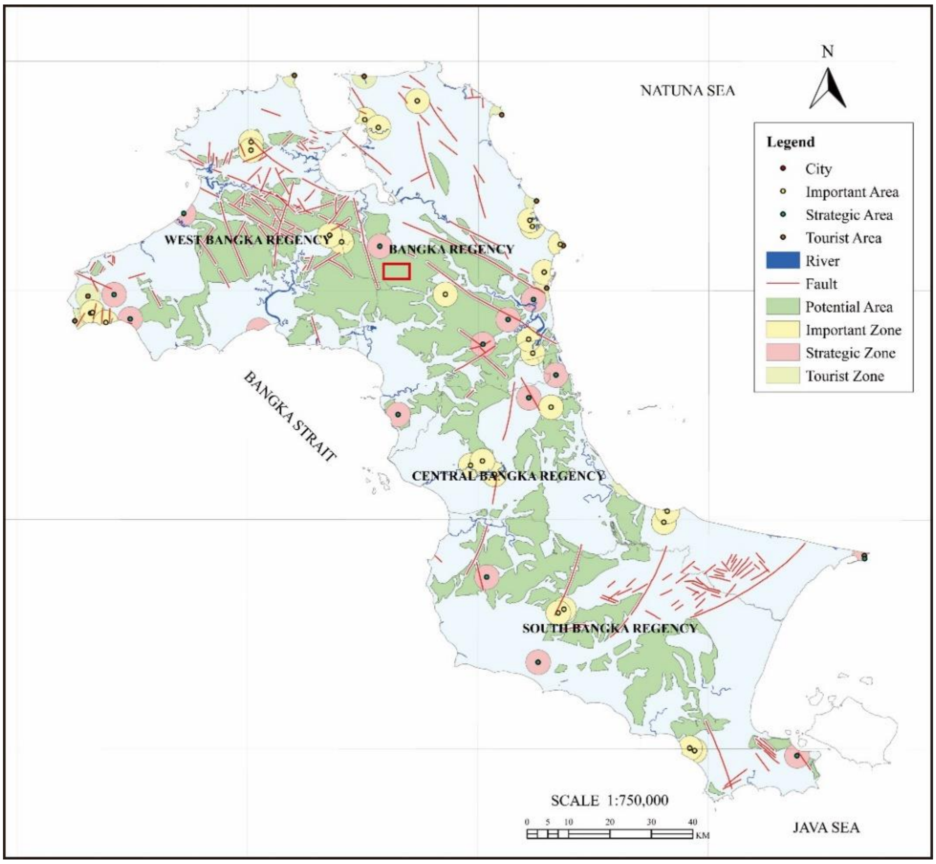

Figure 1. Map of potential site for class 3 landfill facility in Bangka Island (Sucipta et al., 2020)

their homes, the release of radionuclides to the environment can pose internal and external radiation exposure. The considered exposure pathways are radon, inhalation, ingestion (vegetable, milk, meat, and fish), drinking water, and ingestion of soil.

Figure 2 shows an illustration of the layers used in a class 3 landfill facility that must be had for the placement of TENORM waste, according to the Regulation of The Ministry of Environment and Forestry of The Republic of Indonesia No. P.63/Menlhk/Setjen/KUM.1/7/2016 (Ministry of Environment and Forestry, 2016). The use of local natural materials such as bentonite as compacted clay or a protective layer can be applied in this activity (Setiawan and Sriwahyuni, 2018; Sriwahyuni and Setiawan, 2019). This is intended to make the landfill facility to be built more economical and also to increase the local content of the facility.

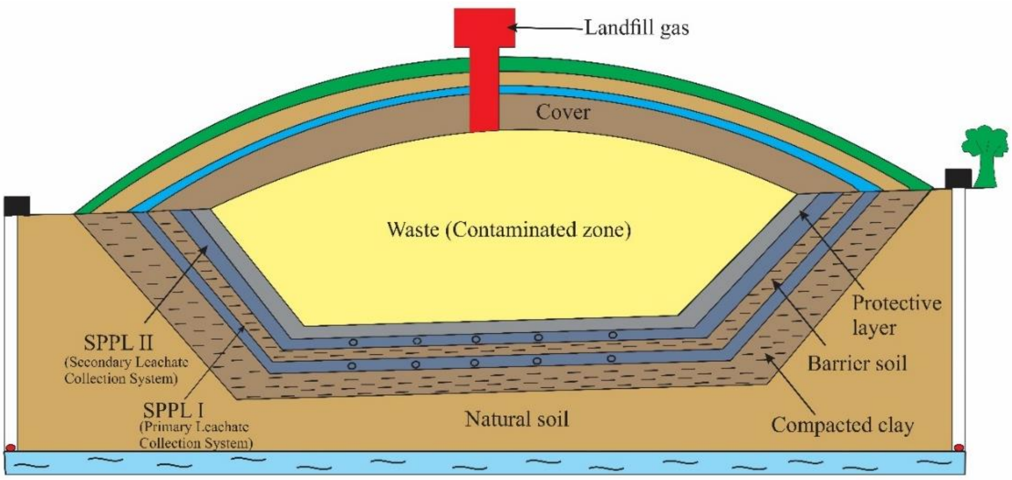

Figure 2. Design of class 3 landfill facility (Ministry of Environment and Forestry, 2016)

2.3 RESRAD OFFSITE version 3.2

RESRAD OFFSITE version 3.2 is a software developed by Argonne National Laboratory which is used to estimate the dose and cancer risk of individuals who are living outside the contaminated zone (dos Reis and da Costa Lauria, 2014). The dose and cancer risk can be estimated using Equation (1) and (2) as follows (Cheng and Yu, 1993):

$$(\mathrm{Dose})_{j,p}(t) = \mathrm{DCF}_{j,p}(t) \times \mathrm{ETF}_{j,p}(t) \times \mathrm{SF}_{i,j}(t) \times \mathrm{S}_i(0) \quad (1)$$

Where; $(\mathrm{Dose})_{j,p}(t)$=effective dose (mrem/year), $\mathrm{DCF}_{j,p}(t)$=dose conversion factor (mrem/pCi), $\mathrm{ETF}_{j,p}(t)$=the environmental transport factor (g/year), $\mathrm{SF}_{i,j}(t)$=source factor, and $\mathrm{S}_i(0)$=soil concentration of radionuclide.

$$(\mathrm{Cancer})_{j,p}(t) = (\mathrm{Intake})_{j,p}(t) \times \mathrm{Sf}_{j,p} \times \mathrm{ED} = \sum_{t=1}^{M} \mathrm{ETF}_{j,p}(t) \times \mathrm{SF}_{i,j}(t) \times \mathrm{S}_i(0) \times \mathrm{Sf}_{j,p} \times \mathrm{ED} \quad (2)$$

Where; $(\mathrm{Intake})_{j,p}$=inhalation and ingestion pathways, M=number of initially existent radio-nuclides, $\mathrm{SF}_{i,j}(t)$=slope factor for radionuclide, and ED=exposure duration (year).

In this study, a conservative approach was estimated using the type of soil, due to the unavailability of site-specific data. According to the authors, these default values in RESRAD code have been carefully and realistically selected from various sources (Yu et al., 2015). To estimate the dose more accurately, site-specific parameter values should be used whenever possible. Therefore, some of the default parameter values were changed according to the site-specific data in Bangka Island (Table 1).

Table 1. Parameters input for the scenario

Parameter	Value	References
Soil concentration		
Ra-226	6.00 Bq/g	Iskandar et al. (2019)
Th-232	10.14 Bq/g	Iskandar et al. (2019)
K-40	0.66 Bq/g	Iskandar et al. (2019)
Contaminated zone		
Area	4,200 m^2	Scenario assumption
Thickness	4 m	Scenario assumption
Length parallel to aquifer flow	100 m	Scenario assumption
Dry bulk/density	2.65 g/cm^3	Iskandar et al. (2019)
Erosion rate	0.20 m/year	RESRAD Default
Total porosity	0.39	Yu et al. (2015)
Effective porosity	0.30	Yu et al. (2015)
Hydraulic conductivity	10^{-2} -10^{1} m/year	Yu et al. (2015)
b parameter	4.05	Yu et al. (2015)
Field capacity	0.25	Yu et al. (2015)
Runoff coefficient	0.37	Yu et al. (2015)
Evapotranspiration coefficient	0.42	Mahfiz et al. (2019)
Precipitation	2.07 m/year	BPS-Statics of Bangka Regency (2020)
Number of unsaturated zone strata	5	Ministry of Environment and Forestry (2016)
Unsaturated zone 1 (Compacted clay)		
Thickness	1 m	Ministry of Environment and Forestry (2016)
Dry bulk/density	1.20 g/cm^3	Yu et al. (2015)
Total porosity	0.42	Yu et al. (2015)
Effective porosity	0.20	Yu et al. (2015)
b parameter	11.4	Yu et al. (2015)
Field capacity	0.45	Yu et al. (2015)
Hydraulic conductivity	40.50 m/year	Yu et al. (2015)
Unsaturated zone 2 (SPPL I)		
Thickness	0.30 m	Ministry of Environment and Forestry (2016)

Table 1. Parameters input for the scenario (cont.)

Parameter	Value	References
Dry bulk/density	3 g/cm^3	Yu et al. (2015)
Total porosity	0.34	Yu et al. (2015)
Effective porosity	0.28	Yu et al. (2015)
b parameter	4.05	Yu et al. (2015)
Field capacity	0.89	Yu et al. (2015)
Hydraulic conductivity	10^4 m/year	Yu et al. (2015)
Unsaturated zone 3 (Barrier soil)		
Thickness	0.30 m	Ministry of Environment and Forestry (2016)
Dry bulk/density	1.20 g/cm^3	Yu et al. (2015)
Total porosity	0.42	Yu et al. (2015)
Effective porosity	0.20	Yu et al. (2015)
b parameter	11.40	Yu et al. (2015)
Field capacity	0.45	Yu et al. (2015)
Hydraulic conductivity	40.50 m/year	Yu et al. (2015)
Unsaturated zone 4 (SPPL II)		
Thickness	0.30 m	Ministry of Environment and Forestry (2016)
Dry bulk/density	3 g/cm^3	Yu et al. (2015)
Total porosity	0.34	Yu et al. (2015)
Effective porosity	0.28	Yu et al. (2015)
b parameter	4.05	Yu et al. (2015)
Field capacity	0.89	Yu et al. (2015)
Hydraulic conductivity	10,000 m/year	Yu et al. (2015)
Unsaturated zone 5 (Protective layer)		
Thickness	0.30 m	Ministry of Environment and Forestry (2016)
Dry bulk/density	1.44 g/cm^3	Yu et al. (2015)
Total porosity	0.45	Yu et al. (2015)
Effective porosity	0.20	Yu et al. (2015)
b parameter	4.38	Yu et al. (2015)
Field capacity	0.35	Yu et al. (2015)
Hydraulic conductivity	4,930 m/year	Yu et al. (2015)
Saturated zone		
Thickness	10 m	Scenario assumption
Dry bulk/density	1.20 g/cm^3	Yu et al. (2015)
Total porosity	0.42	Yu et al. (2015)
Effective porosity	0.20	Yu et al. (2015)
Hydraulic conductivity	100 m/year	Yu et al. (2015)
Cover zone		
Thickness	5 m	Scenario assumption
Drybulk density	1.20 g/cm^3	Yu et al. (2015)
Total porosity	0.42	Yu et al. (2015)
Inhalation rate	8,400 m^3/year	RESRAD Default
Mass loading for inhalation	10^4 g/m^3	RESRAD Default
Soil ingestion rate	36.50 g/year	RESRAD Default
Drinking water intake	510 L/year	RESRAD Default
Irrigation	0.20 m/year	RESRAD Default
Well pumping rate	5,100 m^3/year	RESRAD Default
Leafy vegetable consumption	33 kg/year	BPS-Statics of Bangka Regency (2020)

Table 1. Parameters input for the scenario (cont.)

Parameter	Value	References
Milk consumption	92 L/year	RESRAD Default
Meat consumption	43 kg/year	BPS-Statics of Bangka Regency (2020)
Fish consumption	63 kg/year	BPS-Statics of Bangka Regency (2020)

3. RESULTS AND DISCUSSION

RESRAD OFFSITE 3.2 analysis results were used to determine the effectiveness of class 3 landfill as disposal of TENORM waste from the tin industry in Bangka Island. Table 2 shows that the dose value received by residents at a distance of 100 meters from the contaminated zone before the construction of a landfill facility is 3.13 mSv/year at t=75 years. The main contributor to the high total dose came from Ra-226 radionuclide in the first year to year 6 and the dose decreased to 0.51 mSv/year in year 970. In contrast, Th-232 showed an increasing trend during 970 years with the maximum dose value of 2.18 mSv/year in year 75 to 970. The increasing trend of this graph is caused by the progenies of Th-232 with a half-life from the order of seconds to thousands of years which will show an increasing trend until it reaches secular equilibrium conditions. The half-life of Th-232 as a parent (1.4×10^{10} years) is longer than the half-life of the progenies. Equilibrium conditions are shown by a horizontal graph. When conditions were at equilibrium, the concentration of the progenies was the same or close to the concentration of the parent (Th-232) (Senftle et al., 1956; Rasito et al., 2007). The total dose will decrease when the parent concentration (Th-232) decreases. The concentration will affect the dose calculation. Potassium-40 (K-40) radionuclide does not contribute to the total dose because K-40 had low activity concentrations in the soil sample compared to Ra-226 and Th-232.

Table 2. Dose before the construction of a landfill facility

RN	Dose (mSv/year)									
	t=0	t=1	t=3	t=6	t=12	t=30	t=75	t=175	t=420	t=970
Ra-226	0.92	0.92	0.92	0.92	0.93	0.95	0.95	0.89	0.75	0.51
Th-232	0.08	0.08	0.34	0.78	1.49	2.10	2.18	2.18	2.19	2.21
K-40	0	0	0	0	0	0	0	0	0	0
∑	1.00	1.00	1.26	1.70	2.42	3.05	3.13	3.07	2.94	2.72

By using the class 3 landfill and considering the scenarios established for all exposure pathways after the post-closure, an estimated maximum total dose obtained was 1.84×10^{-2} mSv/year at the first year as presented in Table 3. This dose was below the dose limit for the public of 1 mSv/year by the regulatory body (BAPETEN) (BAPETEN Chairman, 2013). The main contributor to this dose is Ra-226 which is responsible for 100% of the total dose with a downward trend during 970 years, from 1.84×10^{-2} mSv/year to 0.95×10^{-2} mSv/year. In addition, the ionizing radiation dose for radon has a recommended annual effective dose threshold of 10 mSv/year, so the measured total dose from radon remains at a safe level (Harrison and Marsh, 2020). Even though the measured dose is relatively low, radiation exposure should always be monitored carefully. The results of the total dose before and after the construction of a landfill facility are illustrated in Figure 3.

Table 3. Dose after the construction of a landfill facility

RN	Dose ($\times10^{-2}$ mSv/year)									
	t=0	t=1	t=3	t=6	t=12	t=30	t=75	t=175	t=420	t=970
Ra-226	1.84	1.84	1.84	1.83	1.82	1.80	1.75	1.63	1.38	0.95
Th-232	0	0	0	0	0	0	0	0	0	0
K-40	0	0	0	0	0	0	0	0	0	0
∑	1.84	1.84	1.84	1.83	1.82	1.80	1.75	1.63	1.38	0.95

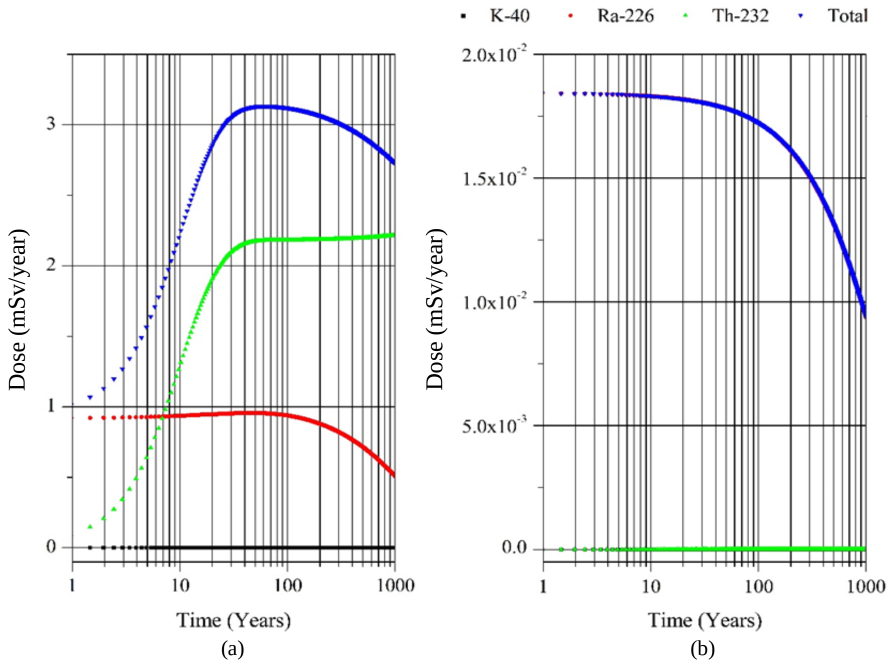

Figure 3. Total dose before (a), and after (b) the construction of a landfill facility

The component exposure pathway contribution to the total dose for each individual radionuclide Ra-226, Th-232, and K-40 during 970 years is shown in Table 4. Ra-226 became the major contributor in the first year through the radon gas (Rn-222) exposure pathways as the first progeny in Ra-226 decay chain with a half-life of 3.8 days (Szabo et al., 2005). Rn-222 will be released into the atmosphere and the dose decreases when the concentration of Ra-226 decreases. Meanwhile, radon gas (Rn-220) which comes from Ra-224 as a progeny of Th-232 tends to contribute only 2% of the total dose in the first year. This is expected due to radionuclide Th-232 taking a longer decay time to produce radon gas, so the dose will be low in the first year and begin to predominate from year 12 to year 970 (Sujo et al., 2004; Tölgyessy and Harangozó, 2005). In general, the total dose derived from the radon gas exposure pathway Th-232 was greater than Ra-226 and K-40, due to the higher activity concentration of Th-232 in tin slag sample.

Table 4. The component exposure pathways before the construction of a landfill facility

RN	Dose (mSv/year)											
	t=0				t=75				t=970			
	Radon		Fish		Radon		Fish		Radon		Fish	
	Dose	%	Dose	%	Dose	%	Dose	%	Dose	%	Dose	%
Ra-226	0.91	96	0	0	0.87	27	0.08	3	0.47	17	0.05	2
Th-232	0.02	2	0	0	2.15	67	0.04	1	2.15	76	0.19	4
K-40	0	0	0	0	0	0	0	0	0	0	0	0

The result of the calculation of RESRAD code shows that the radionuclide concentrations of Ra-226 and Th-232 in the surface water (fish pond) are 12.15×10^{-7} Bq/L in year 75. The result is less than 1% of the total initial concentrations of Ra-226 and Th-232 before being released into the environment. The contributor to the total dose also came from ingestion of fish, which is responsible for 3% from Ra-226 and followed 1% by Th-232. It is estimated that there has been a release of Ra-226 from TENORM waste dump into water bodies. Therefore, the biota in the water becomes contaminated. This can occur because Ra-226 is absorbed into the soil through the leaching process and dissolves into the liquid phase of the contamination zone. Ra-226 will flow with water into the water body (Rajaretnam and Spitz, 2000). Otherwise, Th-232 is difficult to dissolve in the material. Th-232 takes time to decay to be Ra-228 and Ra-224 with respective half-life of 5.75 years and 3.66 days, as ingrowth progenies in the total dose and excess cancer risk for Th-232. Ra-228 and Ra-224 will dissolve and are responsible for water and biota pollution through the leaching process. The ingestion of fish from Th-232 will contribute 4% of the dose and only 2% comes from Ra-226 in year 970. In general, the other pathways were responsible for less than 2% of the total dose during 970 years.

Ra-226 became a major contributor to the total dose after the construction of a landfill facility (Table 5). The simulation shows that the radon gas Rn-222, a progeny of Ra-226, is responsible for 100% of the total dose, which is due to cover erosion. Rn-220, a progeny of Th-232, is estimated to be strongly absorbed and confined by the fine clay mineral fraction in the cover and soil layer of landfill (Ames and Rai, 1978; Melson, 2011). It is suspected that Rn-220 decays before it reaches the surface because the half-life of Rn-220 is only 55 s (Madansky and Rasetti, 1956; Dziurowicz et al., 2017). The construction of a landfill facility acts as a barrier to radionuclide contamination through ingestion of fish and radon gas exposure pathways, as seen in Figure 4.

Table 5. The component exposure pathways after the construction of a landfill facility

RN	Dose ($\times 10^{-2}$ mSv/year)											
	t=0				t=75				t=970			
	Radon		Fish		Radon		Fish		Radon		Fish	
	Dose	%	Dose	%	Dose	%	Dose	%	Dose	%	Dose	%
Ra-226	1.84	100	0	0	1.75	100	0	0	0.95	100	0	0
Th-232	0	0	0	0	0	0	0	0	0	0	0	0
K-40	0	0	0	0	0	0	0	0	0	0	0	0

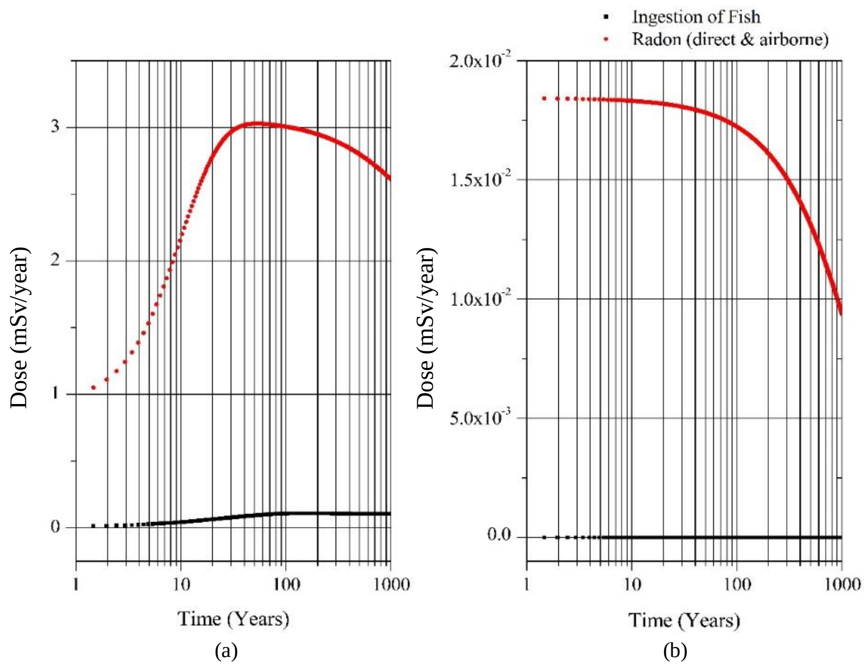

Figure 4. The component exposure pathways before (a), and after (b) the construction of a landfill facility

In addition to the estimate dose absorbed by the body, the simulation results using RESRAD were also used to estimate the excess cancer risk for 970 years. The excess cancer risk for each individual radionuclide Ra-226, Th-232, and K-40 are illustrated in Table 6 and Table 7. The results showed the highest excess cancer risk before and after the construction of a class 3 landfill facility is mainly due to the release of radon gas from tin slag stack, followed by its inhalation. Radon through the diffusion process in the environment will migrate and appear predominantly in locations around the tin slag stack. Radon will stick to dust and small particles in the air that can be inhaled and contribute to internal exposure (Singh et al., 2019).

Several cases have shown that radon can increase the risk of cancer during long-term inhalation due to the release of alpha particles from the decay of radon gas that stays and damages the cells lining the respiratory channel in the lungs. Therefore, preventive action is needed (Lecomte et al., 2014; Vogiannis and Nikolopoulos, 2015). Figure 5 shows the excess cancer risk received by residents was decreased significantly if a class 3 landfill facility was constructed from 5.69×10^{-3} to 6.50×10^{-5}, so the value is close to the recommendation by IAEA (International Atomic Energy Agency, 2011). This indicates that the mitigation strategy in the safety assessment of the construction of a landfill facility is quite effective to prevent the release of TENORM waste to the residents and the environment. Based on the scenario simulation of TENORM waste release by considering the possibility of transporting radionuclide contamination through geological media to the environment, radionuclide contamination can contribute significantly to the acceptance of dose and cancer risk to the residents and the environment. The safety assessment will be useful in the policymaking processes related to the planning development phase and the post-closure of the landfill facility.

Table 6. Excess cancer risk before the construction of a landfill facility

RN	Excess cancer risk ($\times10^{-3}$)					
	t=0		t=75		t=970	
	Radon	Fish	Radon	Fish	Radon	Fish
Ra-226	3.32	0.03	3.15	0.08	1.70	0.04
Th-232	1.68	0.08	2.54	0.03	2.54	0.08
K-40	0	0	0	0	0	0
∑	5.00	0.11	5.69	0.11	4.24	0.12

Table 7. Excess cancer risk after the construction of a landfill facility

RN	Excess cancer risk ($\times10^{-5}$)					
	t=0		t=75		t=970	
	Radon	Fish	Radon	Fish	Radon	Fish
Ra-226	6.50	0	6.35	0	3.46	0
Th-232	0	0	0	0	0	0
K-40	0	0	0	0	0	0
∑	6.50	0	6.35	0	3.46	0

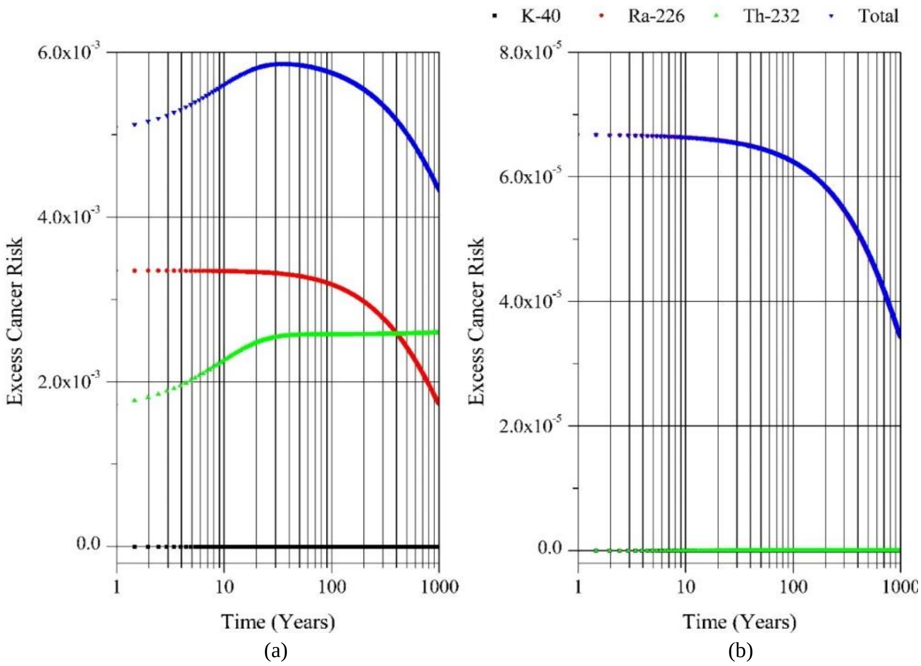

Figure 5. Excess cancer risk before (a), and after (b) the construction of a landfill facility

4. CONCLUSION

The total dose value generated from the two scenarios for the preparation of a landfill facility shows that a class 3 landfill facility is quite effective in reducing the total dose and cancer risk, especially for inhalation of radon gas and ingestion of fish. The main contributors before the construction of a landfill facility came from radon gas exposure and ingestion of fish. The total dose and cancer risk after the construction of a landfill facility was 1.84×10^{-2} mSv/year and 6.50×10^{-5} at the first year, with the primary contributor to the exposure pathway from the release of radon gas. However, regarding the limitation of this study and to decrease the uncertainties in the results, it would be helpful to input more detailed site-specific parameters. This can be explored in future research. Nevertheless, the results obtained from this study can be used by stakeholders in policymaking during the planning and post-closure phases of a landfill facility to protect workers, residents, and the environment from the impact of radiological hazards.

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