Role of geomembrane to prevent water pollution and radiation exposure in landfill for NORM waste from the oil and gas industries

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Abstract. Naturally occurring radioactive materials (NORM) can be concentrated and increased by oil and gas extraction processes. NORM disposal must provide adequate protection to both human health and the environment, which one choice is landfill. The main parameters of concern in the safety of landfills are leachate which could cause water pollution and also radioactive contamination. Leachate can be reduced by using geomembrane in landfill design. In this paper, leaching simulation has been carried out using the required design of class I landfill to see the role of geomembrane to prevent water pollution and reduce radiation dose. Leaching simulations are carried out using the US EPA Hydrologic Evaluation of Landfill Performance software. Simulations of radiation assessment are performed using RESRAD. Landfill is assumed as residential area, with people with people living there and produces their food from that land. From simulation result, appearance of geomembrane can reduce leaching water at bottom layer of landfill from 8.58% of total infiltrated water to 0. For 1 Bq/gram Ra-226, people in landfill with geomembrane are exposed maximum 0.183 mSv/year with radon as dominant exposure. Compared without geomembrane, the maximum exposure is 3.846 mSv/year with drinking water consumption as dominant exposure.

1. Introduction
Oil and gas production processing operations have been known to generate big quantities of naturally occurring radioactive materials (NORMs) at high levels as by-product waste streams [1]. During the production process, NORM flows with the oil, gas and water mixture and accumulates in scale, sludge and scrapings. It can also form a thin film on the interior surfaces of gas processing equipment and vessels. The level of NORM accumulation can vary substantially from one facility to another depending on geological formation, operational and other factors [2].

The main radioisotopes of interest in waste from the oil and gas industry are radium-226 (Ra-226) and radium-228 (Ra-228), respectively formed from the radioactive decay of U-238 and Th-232, and related decay products. For the gas industry, the main radionuclide of interest is lead-210 (Pb-210), which forms a scale within natural gas pipes and machinery. Pb-210 is a gaseous radon-222 (Rn-222) decay product derived from the radioactive decay of Ra-226 [3].

Uncontrolled NORM-related operations can contaminate the environment and pose a threat to human health. To ensure that all aspects of NORM management are highlighted, structured and managed, the following process cycle must be developed well. The process cycle indicates where action and controls may be required to ensure adequate protection of workers, public and the
environment in a practical and cost effective manner. The process cycle is started with NORM monitoring, NORM identification, worker protection, contamination control measures, decontamination, NORM waste interim storage, and the end is NORM waste permanent disposal [4].

Despite the multiple techniques presently available for NORM disposal, NORM waste management, including handling and disposal, is still an interest topic, because all of which are short-term alternatives. Current NORM disposal methods are either landfill disposal, land spreading or underground burial (excavated or abandoned mine) or down hole injection (abandoned wells or disposal wells) or direct disposal into the seabed [5].

The goal of permanent disposal of NORM waste is to create a safe, feasible and budget-effective permanent NORM waste disposal procedure that offers appropriate protection for humans and the environment. The permanent disposal procedure should be intended to avoid contamination of natural resources such as underground water or land that could become component of residential or crop fields in the future, even if it is currently isolated or uninhabited [6].

The Minister of Environment and Forestry Regulation Number P.63/Menlhk/Setjen/KUM.1/7/2016 of Requirements and Procedures for Hazardous and Toxic Waste Disposal in the Landfill Facilities, regulate that NORM waste must be disposed of in class I or class II landfills. The difference in the requirement of the two landfills is the number of geomembranes. Class I landfills have 2 geomembrane layers while class II landfills only have 1 geomembrane layer under the waste layer. While the required capping design for the two types of landfills is the same, they have 1 layer of geomembrane. Figure 1 represents the required layers of class I and class II landfills.

![Figure 1. Required layers of class I and class II landfills.](image)

Geomembranes are also called flexible membrane liners (FML). These liners are constructed from various plastic materials, including polyvinyl chloride (PVC) and high-density polyethylene (HDPE). HDPE is the preferred material for MSW and secure landfills. This material is strong, resistant to most chemicals, and is considered to be impermeable to water. Therefore, HDPE minimizes the transfer of leachate from the landfill to the environment [7]. Although many laboratory tests show that the lifespan of HDPE geomembrane can vary from 100 to 3,000 years, some research discovered that HDPE lifespan was only less than 10 years in landfills [8][9].

In this paper an assessment will be conducted on the effect of the presence of geomembrane in class I landfills on radiation safety that may affect the public in the future. The assessment will use a conservative scenario where landfill is assumed as residential area, with people with people living there and produces their food from that land.
2. Methodology

2.1. Landfill Design
Landfill design to be used is that required in the Minister of Environment and Forestry Regulation Number P.63/Menhk/Setjen/KUM.1/7/2016 [10]. Landfill design parameters that are not listed in the regulation are taken from the PPLI Cileungsi hazardous landfill. PPLI Cileungsi has 1 landfill cell which has been closed with an area of around 6.3 ha. The waste thickness used in this simulation is 12.5 m, this value is obtained from the practical approach of landfill volume data that has been closed with the final cover at PPLI Cileungsi which is 767,761 m$^3$, with a landfill area of 62,693 m$^2$. The thickness of the landfill layer used in this study is as in table 1.

| No | Layers                                      | Thickness (m) |
|----|---------------------------------------------|---------------|
| 1  | Top Soil-Fine Sandy Loam                    | 0.6           |
| 2  | Drainage Layer -Sand                        | 0.3           |
| 3  | Geomembrane-HDPE-2mm                        | 0.002         |
| 4  | Capping Barrier-Barrier Soil                | 0.6           |
| 5  | Temporary Cover-Fine Sandy Loam             | 0.15          |
| 6  | Waste                                       | 12.5          |
| 7  | Protective Layer-Sandy Clay Loam            | 0.3           |
| 8  | Leachate Collection Layer-Gravel            | 0.3           |
| 9  | First Geomembrane-HDPE-2mm                  | 0.002         |
| 10 | Barrier Layer-Barrier Soil                  | 0.3           |
| 11 | Leakage Detection Layer-Gravel              | 0.3           |
| 12 | Leakage Detection Layer-Drainage Net (0.6cm)| 0.006         |
| 13 | Second Geomembrane-HDPE-2mm                 | 0.002         |
| 14 | Base Layer-Barrier Soil                     | 1.0           |
| 15 | Local Soil                                  | 4.0           |

2.2. Hydrology Modeling
The greatest threat to ground water posed by modern landfills is leachate. Leachate is composed of water and water-soluble compounds in the waste that accumulates as water passes through the landfill. This water may be from rainfall or from the waste itself. Leachate can escape from the landfill and contaminate soil and soil water, posing a risk to people and the environment [7]. Leachate formation is influenced by many factors: climate and hydrology, operation and management of landfills, physical characteristics of landfill layers, and internal processes that occur in landfills. The prediction of the amount of formation and composition of leachate is a very complex and difficult work [11]. The Landfill Performance Hydrological Evaluation (HELP) software will be used in this article. The U.S. Environmental Protection Agency (US EPA)'s HELP system (version 3.07) is the most commonly used tool for assessing leachate quantities and studying water balance in landfill layering systems and landfill capping system [12]. It was found that the output of HELP modelling more often overestimated [13], making it suitable for conservative approaches as in this study.

HELP modelling can use daily weather data of 1 to 100 years, evapotranspiration parameters, and soil data and landfill designs. [13]. There are several software that can be selected to produce daily weather forecast synthesis data in the future. LARS-WG is a software that can be used to produce future daily weather forecast data [14][15]. The input parameters of the LARS-WG software are daily rainfall data, daily minimum and maximum temperatures, and also solar radiation. The input data is 30 years of weather data (1984-2013) from the Bogor Climatology Station. Bogor Climatology Station is about 30 km from PPLI Cileungsi. The humidity and wind velocity parameters are taken from the
average weather climatology station in 1984-2013. Other input parameters can be seen in table 2. Leachate rate from hydrological modelling will be an input for radiological modelling. Two scenarios that will be carried out are: scenario 1, landfill has a geomembrane layer as required, and scenario 2 landfill has no geomembrane.

| Parameters                        | Value        |
|-----------------------------------|--------------|
| Evapotranspiration Depth          | 20cm         |
| Maximum Leaf Area Index           | 3.5          |
| Relative Humidity                 |              |
| Quarter 1                         | 87.4 %       |
| Quarter 2                         | 85.1 %       |
| Quarter 3                         | 80.1 %       |
| Quarter 4                         | 84.5 %       |
| Average Wind Speed                | 1 km/hour    |
| Landfill Area                     | 6.3 Ha       |
| Percentage of area where runoff is possible | 100%         |

2.3. Radiological Assessment

Radiological modelling will use RESRAD (onsite) software. RESRAD considers 9 exposure pathways that are very suitable for the exposure pathway that might occur in NORM waste disposal as shown in figure 2. RESRAD has been used in the validation study of the International Atomic Energy Agency Biospheric Model Validation Study II and Environmental Modelling for Radiation Safety (EMRAS) models, and produce consistent results [16]. RESRAD allows only one layer of cover soil to be used. However, for many sites there may be multiple layers overlaying a contaminated region or the waste may be placed under an engineered cover such as a layer of concrete or compacted clay. While such situations cannot be handled directly by RESRAD, these sites can still be analysed with the aid of tools like the Hydrologic Evaluation of Landfill Performance (HELP) software [17].

**Figure 4.** Schematic Representation of RESRAD Pathways

Leachate rate from hydrological modelling will be used in radiological modelling. Leachate (Li) which is input in the RESRAD software is calculated using the formula [18]:

\[ L_i = \frac{1}{\frac{C_i}{d_i} + 1} \]  

(1)
where,

\[ I : \text{Infiltration rate to contaminated zone (m/year)} \]
\[ \theta(z) : \text{volumetric water content of the contaminated zone} \]
\[ T_0 : \text{initial thickness of the contaminated zone (m)} \]
\[ R_{d_i} : \text{retardation factor in the contaminated zone for radionuclide } i \text{ (dimensionless)} \]
\[ \rho_c : \text{contaminated zone porosity} \]
\[ K_{sz} : \text{hydraulic conductivity (m/year)} \]
\[ b : \text{soil-specific exponential parameter} \]
\[ d_s : \text{distribution coefficient for the } i^{th} \text{ principal radionuclide (cm}^3/\text{g)} \]

**Table 3. Input Values for RESRAD**

| Parameter                              | Value   | unit  | Parameter                              | Value   | unit |
|----------------------------------------|---------|-------|----------------------------------------|---------|------|
| Contaminated zone area                 | 63,000  | m²    | Runoff coefficient                     | 0.47    |      |
| Contaminated zone thickness            | 12.5    | m     | Unsaturated zone thickness              | 4       | m    |
| Length parallel to aquifer flow        | 200     | m     | Unsaturated zone density               | 1.7     | g/cm³|
| Cover depth                            | 1.65    | m     | Unsaturated zone total porosity        | 0.427   |      |
| Density of cover material              | 1.6     | g/cm³ | Unsaturated zone effective porosity    | 0.2     |      |
| Cover erosion rate                     | 0.001   | m/year| Unsaturated zone filed capacity        | 0.367   |      |
| Density of contaminated zone           | 1.6     | g/cm³ | Unsaturated zone hydraulic conductivity| 0.0315  | m/year|
| Contaminated Zone erosion rate         | 0.0001  | m/year| Indoor factor                          | 0.5     |      |
| Contaminated Zone total porosity       | 0.671   | -     | Outdoor factor                         | 0.25    |      |
| Contaminated zone field capacity       | 0.292   | -     | Vegetable and fruit consumption        | 63      | kg/year |
| Contaminated zone hydraulic conductivity| 315     | m/year| Meat and poultry consumption           | 30      | kg/year |
| Evapotranspiration coefficient         | 0.51    | -     | Milk Consumption                       | 16.5    | litre/year |
| Wind speed                             | 1       | m/s   | Fish Consumption                       | 30      | kg/year |
| Precipitation                          | 3.8     | m/year| Drinking water intake                  | 510     | litre/year |

The residential scenario at the landfill location is designed to evaluate highly conservative scenarios. In this scenario, it is assumed that someone lives in a landfill location; produce most of the food at that location, including vegetables, milk, meat and fish; and use ground water from locations for household and agricultural purposes. This scenario may not represent realistic landfill use in the future, but this assumption is usually used by risk assessors in evaluating potential doses for people who are expected to receive the greatest damages from a system [3]. Residents are assumed to spend 18 hours every day at landfill locations (12 hours spent indoors), 365 days per year. Possible exposure pathways for residents at landfill sites include external and indoor exposure to radon inside and outside. Other exposure pathways that are also evaluated are inhalation of contaminated particulates;
accidentally eating contaminated soil; and consumption of plants, milk and meat planted or hunted in contaminated locations. For all exposure routes modelling is carried out for the next 1000 years. Modelling is done for radioisotopes which are of concern in the oil and gas industry, Ra-226, Ra-228 and Pb-210 with activity concentration 1 Bq/gram. Input parameters are listed in table 3, others use RESRAD default values.

3. Result and Discussion
For scenario 1, it is found that class I landfill design has a good ability to hold water entering landfills. The average leachate rate that comes out of the landfill base layer is 0.00007 mm/ year. The infiltration rate to the waste layer is 0.98157 mm/year. This is because the water that tries to enter the waste layer is held by the geomembrane in the landfill cover layer. For scenario 2, it is found that landfills have an increasing average value of leachate rate in the landfill base layer of 321.5 mm/year or 8.59% of the average rainfall value. With the loss of geomembrane in the landfill cover layer, the infiltration rate that enters the waste layer is 683.3 mm/year or 18.25% of the rainfall. From this fact it can be concluded that the presence of geomembranes is very important in preventing contamination. Comparison of the results of modelling the two scenarios is in table 4.

| Scenario I | Scenario II |
|------------|-------------|
| Rate (mm/year) | Total volume (m³/year) | Percentage to precipitation | Rate (mm/year) | Total volume (m³/year) | Percentage to precipitation |
| Precipitation | 3,744.93 | 243,420.6 | 100 % | 3,744.93 | 243,420.6 | 100 % |
| Leachate from Capping Barrier | 0.98157 | 63.802 | 0.0262 % | 683.3 | 44,414.56 | 18.25 % |
| Leachate from protective layer | 0.98146 | 63.802 | 0.0262 % | 683.251 | 44,411.31 | 18.24 % |
| Leachate from Barrier layer | 0.00011 | 0.007 | 0 % | 321.56 | 20,901.39 | 8.59 % |
| Leachate from base layer | 0.00007 | 0.005 | 0 % | 321.51 | 20,898.47 | 8.58 % |

Infiltration rate from scenario 1 is 0.98157 mm/year and from scenario 2 is 683.3 mm/year. By using equations 1 to 3, the input values for leachate rate for each radionuclide will be obtained as in table 5.

| Element | Distribution Coefficient cm³/gram | RESRAD Leach Rate Input (1/year) |
|---------|----------------------------------|----------------------------------|
| Radium | 70 | 4.9x10⁴ |
| Timbal | 100 | 3.4x10⁴ |
| Thorium | 60,000 | 5.7x10⁷ |

From the simulation that has been done using RESRAD software, it was found that landfills with geomembrane (scenario 1) resulted in smaller doses than landfills without geomembrane (scenario 2). Very significant differences occur for radionuclides Ra-226 and Pb-210. The maximum radiation dose received by residents from radionuclide Ra-226 in landfills with geomembrane is 0.183 mSv/year, whereas in landfills without geomembrane it increases to 3.846 mSv/year. The maximum radiation dose received by residents from radionuclide Pb-210 in landfills with geomembrane is 1.909x10⁻¹⁵ mSv/year, while in landfills without geomembrane it increases to 2.733x10⁻¹¹ mSv/year. Comparison of the maximum doses for each radionuclide is shown in table 6.
Table 6. Maximum doses

| Scenario 1 | Scenario 2 |
|------------|------------|
| Dose from 1 Bq/gram (mSv/year) | Dose from 1 Bq/gram (mSv/year) |
| Ra-226 | 0.183 | 3.846 |
| Ra-228 | 7.28x10^{-8} | 7.27x10^{-8} |
| Pb-210 | 1.91x10^{-15} | 2.73x10^{-11} |

Figure 5. Dose each pathway from Ra-226 in landfill with geomembrane (scenario 1)

Figure 6. Dose each pathway from Ra-226 in landfill without geomembrane (scenario 2)

Figure 7. Dose each pathway from Pb-210 in landfill with geomembrane (scenario 1)

Figure 8. Dose each pathway from Pb-210 in landfill without geomembrane (scenario 2)

The dominant exposure pathway that occurs in scenario 1 for radionuclide Ra-226 is radon gas exposure, while in scenario 2 is consumption of drinking water as shown in figure 5 and figure 6. The dominant exposure pathway that occurs in scenario 1 for radionuclide Pb-210 is external exposure, whereas in Scenario 2 is drinking water consumption as shown in figure 7 and figure 8.

This shows that the presence of geomembrane can prevent groundwater pollution and indirectly reduce radiation exposure. The practice carried out at PPLI Cileungsi, installed geomembrane always consists of 2 layers to minimize the risk of damage to the geomembrane. This practice needs to be exemplified for those who will build landfills or can also be used as a consideration for improving future regulations. Other studies should also be conducted to find out what parameters affect the safety of radiation on NORM waste disposal, some studies have found that landfill cover thickness, landfill cover density, rainfall and erosion rate affect the safety of radiation in NORM waste landfills [19][20].

4. Conclusion
The presence of geomembrane can prevent groundwater pollution and indirectly reduce radiation exposure. Landfill with geomembrane arise smaller risk of radiation exposure than landfill without...
To mitigate geomembrane failure, it is necessary to apply good quality control system and redundancy action. The required design for class I landfills is sufficient to ensure radiation safety in the disposal of NORM waste from the oil and gas industry.

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