Urania
Jurnal Ilmiah Daur Bahan Bakar Nuklir

Beranda jurnal: https://ejournal.brin.go.id/urania

RESRAD PARAMETER SENSITIVITY SIMULATION TO ASCERTAIN LOCAL PARAMETERS FOR SAFETY ASSESMENT ON BANGKA ISLAND

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(Submitted: 03–06–2025, Revised: 07–08–2025, Accepted: 01–09–2025)

ABSTRACT
RESRAD PARAMETER SENSITIVITY SIMULATION TO ASCERTAIN LOCAL PARAMETERS FOR SAFETY ASSESSMENT ON BANGKA ISLAND. Tin slag and waste generated by tin processing often contain Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM), which pose significant radiation hazards to workers, the public, and the natural ecosystem. To mitigate these risks, the development of a dedicated landfill facility is crucial for managing the radiological impact. This study analyzes the implications of storing TENORM waste, both prior to and following the construction of a landfill. The challenge of TENORM management persists, primarily due to the presence of long-lived radionuclides include uranium-238 (U-238), thorium-232 (Th-232), and potassium-40 (K-40), which are often inadequately handled by industry. To address this, a landfill design was proposed and evaluated by software simulation using RESRAD-Offsite 4.0 software. The default parameter values are multiplied by 0.25, 0.5, 1, 1.5, and 1.75. The resulting dose calculations are compared to those using the default value. If the difference is below 10%, it is considered low sensitivity, between 10% and 1000%, medium sensitivity, and above 1000%, high sensitivity. The reserch aim to optimize safety and resource allocation,. From 194 parameters were simulated, with approximately half exerting a significant influence on dose estimations. This study used software simulations to determine the level of influence each parameter has on dose calculations. Parameters who have low sensitivity are soil to plant transfer factor for Th and U, radionuclide spesific release for Th, U, and K, medium sensitivity are precipitation, total porosity saturated zones, high sensitivity are Fraction of time spent on primary contamination at indoor and fraction of time spent for livestock.

Keywords: radiation dose, safety assessment, RESRAD, parameter sensitivity, TENORM.

INTRODUCTION

The tin industry on Bangka Island encompasses a diverse array of stakeholders, from local home-based enterprises to small, medium, and large-scale businesses. Renowned for its significant capacity, Bangka Island stands as a prominent hub for the tin industry [1]. The tin bearing rock spread from Southern China, Burma, Thailand, West Malaysia to Indonesia. This line is well known as The South Asian Tin Belt Zone [2]. Tin has been mined from the land for centuries, but its extraction has now extended to coastal areas; this expansion has led to increased profits while also worsening environmental issues [3]. Tin exploration is carried out not only on land but also in marine environments, as both sources are essential for obtaining high-quality tin ore with optimal purity and value for processing. If the management of these wastes in landfills is not adequately controlled, it could cause environmental pollution, potentially exposing people directly involved in tin mining, as well as humans, wildlife, and vegetation, to radiation [4].

To obtain pure tin, the tin ore extracted from natural sources must undergo a series of lengthy and complex processes to remove impurities and refine the material. The processes are divided into two steps: the exploration process to discover tin locations and the exploitation process to get and extract pure tin from tin ore[4]. These steps start from collecting tin ore from the soil, forest, river, and sea. After gathering tin ore, the next step involves processing it through several stages, including washing, separation, processing, smelting, and refining, to extract and purify the tin for use in various applications [5].

Besides tin itself, tin ore contains other valuable mineral elements, such as monazite, zircon, xenotime, ilmenite, and others. These minerals also contain radioactive substances such as Uranium-238, Thorium-232, Potassium-40, and their decay products. The issue is that Uranium-238 and Thorium-232 possess extended half-lives and can pose risks to humans and the environment if not managed properly [6]. Radioactive elements that exist naturally in the environment are known as NORM, which stands for Naturally Occurring Radioactive Materials. The concentration of radioactivity in NORM increases with human activities such as exploration and mining processing [7]. When human activities concentrate NORM, it becomes TENORM (Technologically Enhanced Naturally Occurring Radioactive Material). The tin industry is one of the producers of TENORM, making it essential to focus on radiation safety for workers, the society, and the environment [8].

Regulations regarding TENORM are outlined in Government Regulation (PP) No. 52 of 2022 concerning the safety and security of nuclear mining. Article 44 states that permit holders who no longer store TENORM waste are required to carry out permanent disposal [9]. This is further affirmed in the Bapeten Chairman’s Regulation No. 9 of 2009 concerning measures to prevent exposure from TENORM waste. Article 4 states that TENORM producers must conduct radiation safety analyses for TENORM at each location they own or control within their jurisdiction [10].

Radiation protection judgment must follow two principles, the principles are as low as reasonably achievable (ALARA) and principles of JOD (justification, optimization, and dose limitation).In Bangka, numerous tin tailings and waste storage sites are poorly managed, posing a risk of radiation exposure to communities beyond the immediate work areas. This hazard is exacerbated by moderate to heavy rainfall, as rainwater may carry radioactive elements that leach from the storage sites [11]. Workers in tin factories and mines have the potential for high radiation exposure, because they are exposed to minerals containing TENORM and radioactive tin by-products. These workers are at risk of receiving radiation doses exceeding the threshold set by BAPETEN for radiation workers, which is 20 mSv/year, because they are more controlled. The general public is also at risk of receiving doses exceeding the limit set by BAPETEN, which is 1 mSv/year, if radiation safety measures are not implemented properly [12]. Given these potential risks, radiation safety must be a top priority. Therefore, workers and the surrounding community must be involved in a comprehensive radiation protection program [7]. This program must meet safety standards that are essential to protecting the health and well-being of all individuals potentially exposed to radiation from the site[13].

A method to mitigate radiological risks to both the community and the environment is to establish a TENORM management system and construct at least a class II landfill, following the guidelines outlined in the Regulation of the Minister of Environment and Forestry Number 63 of 2016, for handling tailings and tin waste [14]. This study will discuss the simulation of sensitivity parameters and the assessment of the radiation doses that will be absorbed by workers and the public, along with their implications for cancer risk and its impact on human health [15].

The problem of TENORM waste that cannot be processed anymore and still contains high radioactive substances is whether the waste will remain stored in the work area or disposed of in accordance with applicable regulations. If it is decided to be stockpiled, it is necessary to determine the most appropriate location for the landfill site, the party who will build it, and how safe the landfill is after it is closed [16]. This issue needs to be addressed immediately on Bangka Island, especially in Indonesia. Many of the proposed landfill categories and alternatives are not always founded on scientific evaluations or risk assessments from engineering and medical standpoints. Nevertheless, some of these methods continue to be widely used in landfills across the globe [17].

Bangka Belitung Island, in particular, and Indonesia as a whole, have uncertain data regarding the inventory of TENORM waste [18]. This condition will make Indonesia have no precession data to know the amount of TENORM waste and waste production each year, so that its management is ineffectiveness and not comprehensive. Inventory data must at least include the volume of waste and the level of radioactivity of TENORM waste [19].

The TENORM landfill facility is designed to store waste safely and prevent radiation exposure to humans and the environment. The selection of the landfill site aims to ensure radiation safety, while complying with applicable regulations, which is one of the main focuses of this study. This study refers to various standards set by the IAEA, as well as guidelines and recommendations from international experts. [20]. In Indonesia, TENORM waste management must be carried out in a coordinated and integrated manner, from upstream to downstream. The landfill facility is designed to accommodate various types of waste, with increasingly higher quality and safety standards in proportion to the level of hazard of the waste being disposed of [17].

In the context of radioactivity, tin slag is a waste with a very low level of radioactivity, which requires special storage, such as a designated landfill. TENORM waste with an activity concentration of more than 1 Bq per gram, generally from Uranium and Thorium series, must be disposed of in a landfill designed to manage and accommodate the leachate produced, so that the leachate remains controlled even after the facility is closed [21]. This landfill is equipped with a system to avert the release of hazardous materials and maintain safety standards for long-term environmental protection. Proper classification and disposal are essential to minimize the risk of radiation exposure [22].

The smelting process that generates TENORM waste is categorized as hazardous waste, specifically in category 2, and originates from certain sources. The storage requirements for this type of waste are detailed in the Minister of Environment and Forestry's Ordinance Number 63 of 2016 [14]. Because TENORM waste is hazardous, it is essential to manage, store, and handle it with utmost caution to make sure safety and full compliance with applicable regulations. Proper handling is crucial not only for meeting legal standards but also for minimizing the serious environmental and health risks linked to improper disposal or management of TENORM waste, which highlight the potential impacts on human health, taking into account accumulation in organisms, transfer through the food chain, radiation exposure dangers, and environmentally sustainable mitigation and management strategies for landfill facilities [23].

This research utilized the RESRAD OFFSITE software version 4.0 to assess the radiological dose estimation. This study also distributed sensitivity parameters and their impact on the estimated dose received and the risk of cancer experienced by the community[24]. Parameters with high sensitivity will have a major impact on the calculation of dose and cancer risk, while parameters with low sensitivity will have a small impact. The sensitivity criteria low, medium, and high are based on the author's grouping.

The history of Resrad Offsite development began with the addition of a submodel for radionuclide accumulation in off-site soil (BIOMOVS II 1995) into RESRAD-ONSITE, as well as including an advection-dispersion submodel to model groundwater transport (BIOMOVS II 1996). This advection-dispersion submodel is designed to estimate the movement of radionuclide decay offspring during the transport process from the parent radionuclide. So that RESRAD-OFFSITE becomes an independent software that is able to receive data on the time of radionuclide release from radionuclide-contaminated soil [24]. In addition, this software also includes submodels for atmospheric and surface water transport, and can evaluate radiation doses and cancer risks in individuals exposed to radiation, both inside and outside the primary contamination. RESRAD-OFFSITE uses numerical techniques to estimate concentrations, doses, and risks over time. This software calculates and predicts the conditions and doses received by the community around the landfill environment since the landfill was opened until 100,000 years after the landfill was closed [19].

METHODOLOGY

This paper guideliness make safety assessment from model which computed by Resrad Offsite Software. Modeling on software will be made by research to sensitivity each parameter in Resrad Offsite Software. Research will estimate The influence of each parameter on the estimated dose calculation can be assessed to determine whether its impact is high, medium, or low. Based on these results, it can be identified which parameters require local data or onsite data, which can rely on regional data, and if don't find the data may use default values. Default values represent the fair value of a parameter as provided by RESRAD, based on results from in-depth research and various scholarly references.

The landfill facility planned to build at Bangka Island, which was chosen because of its proximity to the tin processing center. The geological layers of Bangka Island are primarily made up of the Tanjung Genting Formation, which consists of clay deposits, which can serve as engineering barriers for landfill facilities[1]. Clay has the ability to retain fluid flow, making it an ideal natural material to reduce radionuclide leaching [24].

The landfill layer from top to bottom are cover layer, consisting of vegetation, topsoil, and compressed clay, helps reduce exposure, prevent water infiltration, manage gas emissions, and promote plant growth. It must be at least 30 cm thick and free from contaminants. The Leachate Collection and Transfer System (LCTS) requires 30 cm of granular soil with low hydraulic conductivity, while a soil barrier, like compacted clay or Geosynthetic Clay Liner, must meet specific conductivity standards. The geomembrane layer, made from HDPE, ensures long-term durability, and the base layer, a compressed clay matrix, needs to be at least 1 meter thick with designated hydraulic conductivity levels [25].

a. Software Simulation

This study utilized the RESRAD Offsite 4.0 software to simulate and estimate the radiation dose received by the community around the location. RESRAD version 4.0 was developed by Argonne National Laboratory in Illinois. RESRAD-OFFSITE is a development of RESRAD-ONSITE, which was previously used to predict the radiation dose received by radiation workers due to exposure to radioactive substances at the facility. While RESRAD-OFFSITE is specifically designed to evaluate the radiation dose received by the community living around the facility [19].

In this safety assessment simulation, input data were obtained from multiply 0.25, 0.5, 1, 1.5, 1.75 of default values from RESRAD software all of which default values were collected from various sources carefully and accurately [27]. Low sensitivity is defined as having a maximum difference of 10% in dose values when comparing parameter values of 0.25x of the default and 1.75x of the default. Medium sensitivity corresponds to a difference of approximately 10% to 1000% under the same parameter range. High sensitivity is characterized by a difference greater than 1000% between the dose values at 0.25× and 1.75× the default parameter. Based on these findings, this study provides recommendations to all stakeholders who involved in the tin industry to reduce potential radiological risks and ensure that radiation exposure to the community remains within safe limits, in order to prevent radiation doses that exceed acceptable thresholds [18]. However, to obtain more precise results, it is important to use local parameter because have high sensitivity like precipitation, Fraction of time spent on primary contamination at indoor. from the research location so that the results obtained are more accurate and accountable. To determine which data should use local parameter values and which can use regional parameter values or even default values such as Intake to Animal Product Transfer Factor U-238, Soil to Plant Transfer Factor for Th and U, Radionuclide Spesific Release for Th, U, and K. This sensitivity test purpose to identify the parameters that most significantly impact dose calculations and excess of cancer risk [27].

b. Data Input Parameter

The sensitivity of the RESRAD parameters is analyzed to assess the impact of each parameter on the dose outcomes. The input data were based on the software's default values, using variations of 25%, 50%, 150%, and 175% of the default. Any 194 parameters was simulated like distibution coeffient, transfer factor, storage times, etc by this study. The parameters value would be seen the impact to dose calculation results then compare dose calculation with simulation value and dose calculation with default value.

c. Simulation Process

The simulation process comprised several steps, starting with the entry of input data into the RESRAD Offsite 4.0 software. Site-specific conditions and parameter sensitivity values were integrated into the landfill model. Simulations were conducted for timeframes of 100, 500, and 1000 years to assess parameter sensitivity. The software generated outputs such as estimated radiation doses to nearby populations and projected excess cancer risks based on varying parameter values. After completing the sensitivity simulations, the results were analyzed to detect trends and assess the safety of the landfill design. Graphs were created to illustrate dose variations over time and to show the contribution of individual radionuclides[28].

The results of the sensitivity simulations were carefully analyzed to assess how changes in parameter values affect the calculated dose. Maximum dose levels were compared to those obtained using the default parameter values. This analysis helps determine whether specific parameters require locally sourced data or if regional or default values are sufficient. By identifying which parameters significantly influence the results, the study can be made more efficient, as not all inputs need to be replaced with local data[29].

RESULT AND DISCUSSION

This study analysis how parameter sensitivity to dose and cancer risk result. Some parameter have high impact to dose result and other parameters have low impact to the dose result like the fraction of time spent on primary contamination (indoor) parameter, Fraction of time spent, fruit parameter, and Fraction of time spent, livestock. The figure 1, figure 2, and figure 3 show ratio between dose value which results by parameter 25% of default, 50% of default, 150% of default, 175% of default and default. 194 parameters have been simulated in this research. About 97 parameters such as deposition velocities thorium, soil to plant transfer factor uranium, radionuclide spesific release K-40 did not change the dose result (same with dose gotten from default value) and had no sensitivity when simulated by certain values and in other side about 97 parameters such as intake to animal product transfer factor U-238, precipitation, fraction of time spent on primary contamination at Indoor have an effect on changes in the estimated dose value and are therefore considered to have a sensitivity value.

The Intake to Animal Product Transfer Factor U-238 exhibits extremely low sensitivity, with only very small change of 0.00001 over a period of 1000 years. This signifies that alterations in this parameter have a negligible impact on the overall radiation dose calculation. The reason for its low sensitivity lies in the fact that it represents a small fraction of the total radiation exposure. The transfer of U-238 from environmental sources into animal products is minimal, with only a tiny amount entering the food chain. Moreover, once U-238 is incorporated into animal products, it becomes diluted, further reducing its potential impact

[27]. In comparison, other exposure pathways, such as radon inhalation or direct contact with contaminated soil, contribute far more significantly to the overall radiation dose. Consequently, variations in the U-238 transfer factor result in only a modest effect on the final radiation dose estimates for the community. which can be seen in Figure 1.

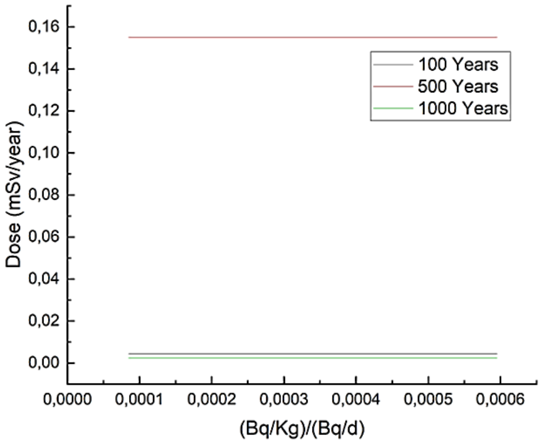

Figure 1. Correlation between intake to animal product transfer factor U-238 and dose.

At 100 years the dose value don't change along with the increase in the intake to animal product transfer factor value, at 500 years the dose value don't change along with the increase in the intake to animal product transfer factor value. On 1000 years the dose value changed very small starting from the Intake to Animal Product Transfer Factor U-238 value of 0.25 x default and 0.5 default resulting in a dose calculation of 0.00239 mSv/year then increasing slightly to 1x default and 1.5x default resulting in a calculation of 0.0024 mSv/year then decreasing slightly again at 1.75x default to 0.00239 mSv/year.

The precipitation parameter has medium sensitivity. It change 0.388 mSv/years at 0.25 of default to 0.091 mSv/year at 1.75 of default on 500 years. This means that the precipitation parameter has decreased about 426% and belong to medium impact on the final dose calculation. So that large changes in this parameter will have amedium effect on the estimated dose that will be received by the community. which can be seen in Figure 2.

Rainfall serves as a natural mitigator of radiation exposure at landfill sites, harnessing a blend of processes to alleviate harm. The rain dissolves radionuclides from the surface of soil and waste, carrying them deeper into the earth or into groundwater, thus reducing their surface concentration and lowering radiation exposure. Landfills containing TENORM waste also emit radioactive gases like radon through decay, while rain further aids by washing away radioactive particles from the surface [30]. This combination of leaching, dilution, and surface purification significantly influences the movement of radiation. Precipitation, especially during periods of heavy rainfall, playing a crucial part in influencing behavior and distribution of radiation across landfill areas, offering a natural mechanism to mitigate its impact [30].

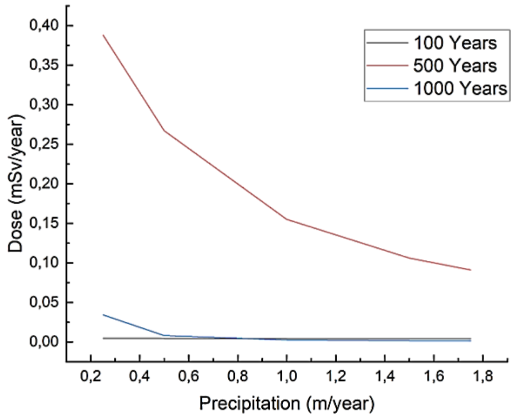

Figure 2. Correlation between precipitation and dose.

An example of a parameter with high sensitivity is the fraction of time spent on primary contamination (indoor) parameter on occupancy input, where a fraction of 0 over a period of 100 years results in an estimated dose of 0.00429 mSv/year, and a fraction of 1 over the same time period results in an estimated dose of 0.473 mSv/year. When calculated as a percentage, the sensitivity reaches 11,025.64%. As an illustration, it is presented in Figure 3.

The fraction of time spent on time spent indoors in areas with primary contamination is a critical parameter in RESRAD-OFFSITE, having a major impact on radiation dose. It represents the amount of time an individual, usually a resident, spends in a contaminated indoor environment. A higher fraction of time spent indoors generally results in a greater calculated dose, as it increases exposure to primary pathways like radon inhalation, resuspended particles, and indoor gamma radiation. While indoor environments may offer some shielding from external gamma radiation, they can also trap airborne contaminants, amplifying the risk of being exposed. Therefore, this parameter plays a, crucial part in determining radiation dose evaluations particularly in scenarios where indoor exposure contributes significantly to the overall radiological risk [31].

This value indicates how much time an individual spends inside buildings affected by radioactive contamination. Primary contamination refers to radioactive substances that have accumulated indoors, often due to fallout or other sources. What makes it important is that that people typically spend a substantial amount of time inside, where the confined environment and limited air circulation can increase the risk of radiation exposure. The fraction measures the time spent within these impacted indoor areas and has a direct effect on radiation exposure. For instance, if a person spends 80% of their time in contaminated indoor spaces, the fraction would be 0.8 [31]. This value is used to estimate the potential internal radiation dose based on the time spent in these high-risk areas. Due to its high sensitivity, this parameter can greatly impact the final dose calculation, so accuracy in gathering this data is essential.

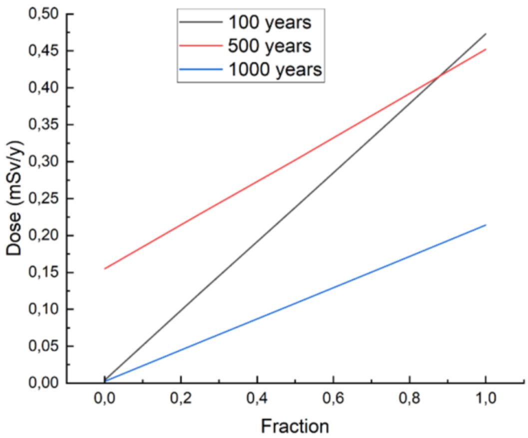

Figure 3. Correlation between fraction of time spent on primary contamination at indoor and dose.

CONCLUSION

TENORM waste needs careful handling because it can affect people and the environment over a long time. This study focuses on building disposal facilities for this waste and testing their designs with the RESRAD-Offsite 4.0 software. The software was ran sensitivity tests on 194 different factors and found that only about half actually influence radiation dose estimates in a meaningful way. Some factors, like how much uranium-238 gets into animal products, barely change the estimated dose even over 1,000 years. This means that not every exposure route is equally important when thinking about radiation risks.

On the other hand, some factors, like rainfall, has parameter sensitivity 426% and belong to moderate effect since they can help reduce radiation exposure naturally. The most influential factor by far is the fraction of time spent on primary indoor contamination parameter. It has sensitivity 11,025.64% because of contamination was major factor can change dose estimates dramatically. This shows how important it is to consider human behavior in radiation risk assessments. Because of this, when designing waste management strategies, it's essential to focus on the parameters that have the biggest impact on radiation doses. Doing so helps protect both the public and the environment more effectively.

ACKNOWLEDGEMENT

The research fund to complete this study was supported by HITN's budget of Research Organization for Nuclear Technology (ORTN), Grant No CFJRC-ORTN2025-1182453318079. Head of Physics Departement IPB University, Head of Magister Biophysics Study Program IPB University, Head of Research Center for Nuclear Material and Radioactive Waste Technology, Coordinator of Research Group of Radioactive Waste Technology who supported writers to complete this paper.

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