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Analysis of Cs-137 Diffusion in Clay Soil and Kaolin from West Kalimantan with Groundwater Saturation

Muhammad Haidar Kurniawan[1], Noor Anis Kundari[1], Nurul Efri Ekaningrum[1]

[1]Politeknik Teknologi Nuklir Indonesia, Jalan Babarsari PO Box 6101 YKBB, Yogyakarta, Indonesia

**Corresponding Author: Muhammad Haidar Kurniawan*
Email: haidark33@gmail.com

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Abstract

Electricity demand in Indonesia is increasing along with economic and population growth. The plan to build a nuclear power plant (NPP) in Kalimantan needs to be accompanied by support facilities such as disposal. Research on disposal facilities in West Kalimantan is crucial because of its proximity to the planned NPP, and using local materials like kaolin and clay will be more economical. In this study, compacted clay and kaolin layers were used as part of the engineered barrier at the disposal site. The goal is to prevent the release of Cs-137 from the facility into the unsaturated zone. XRD, XRF, and ICP-OES were used to characterize the clay and kaolin studied. Analysis revealed many absorbent minerals suitable for the engineered barrier at the disposal site.To evaluate the diffusion coefficient (Da) of Cs-137 in compacted clay and kaolin samples, a vertical diffusion model was employed. The diffusion coefficient was measured in a diffusion column unit with varying times and densities. Fick's law equation was used to calculate the Da value for the samples. The results showed that the diffusion coefficient for kaolin ranged from 2.75 x 10-12 to 3.96 x 10-12 m^2/s, and for clay from 1.62 x 10-12 to 2.92 x 10-12 m^2/s. In clay and kaolin samples, density affected the diffusion rate; higher density resulted in a lower Da value. However, time did not impact the Da value. The diffusion coefficient in kaolin was twice as fast as in clay samples.In the safety assessment experiment with RESRAD Offsite, a 0.2 m kaolin layer was sufficient.

Introduction

Industrial and medical activities in Indonesia currently produce radioactive waste. Radioactive waste management in Indonesia involves temporary storage. In this case, the Directorate of Nuclear Energy Facilities Management (DPFK - BRIN) is responsible for managing all radioactive waste sent to BRIN. Most of this waste is stored in the Radioactive Waste Management Installation (IPLR), while for this study the scope of discussion is related to Low and Medium Level Radioactive Waste that will be stored in the Near Surface Disposal in the future (Wisnubroto et al., 2021; Giannakopoulos et al., 2021; Amiard, 2021; Leva, 2021; Solieri et al., 2025). In this study, the tracer radionuclide Cs-137 will be used, which is representative of various types of radionuclides stored at DPFK-BRIN. The total activity of Cs-137 (solid waste) stored at DPFK-BRIN is 24.4% of the total activity of all existing radionuclides. This figure is the second highest activity value after Ir-192 (IPLR-DPFK-BRIN, 2023)

The aspects analyzed in the development of disposal facilities are the determination of the location of the disposal facility site that follows the Nuclear Power Plant Development Program (if using the co-location principle with a specific site proposed by the National Authority).

Another aspect is the safety of the disposal design itself in the event of a leak of radioactive waste stored in it into the environment around the disposal site after the waste has been stored for hundreds of years (Darda et al., 2021; Keerthi et al., 2024; Korede et al., 2023). This aspect is part of the research that will be conducted by the Center for Research and Technology of Nuclear Materials and Radioactive Waste (PRTBNLR). Surveys of prospective disposal site locations have been conducted in various regions in Indonesia for a long time, starting from 1989 until now (Syaeful et al., 2014; Kurniawan et al., 2023) and one of the candidates is the prospective site at DH-2 Serpong Nuclear Area (KNS). This location is an official determination from the government (Ekaningrum, 2022) with special considerations, namely close to Interim Storage (IS) 1 and 2 which are temporary storage places for LRA from all over Indonesia. Thus, in addition to facilitating the transportation process, it can also reduce potential burdens in the form of transportation costs and considering the acceptance from the community, especially because the acceptance of nuclear energy in Indonesia still causes controversy in several regions in Indonesia (Herawati & Sudagung, 2020; Aditya et al., 2025; Ho et al., 2022; Wisnubroto et al., 2025).

Disposal facilities have many types depending on the type of Radioactive Waste stored (IAEA, 2011). The type of disposal planned to be built in the Serpong Nuclear Area, KST BJ. Habibie, BRIN is Near Surface Disposal (NSD) (Ekaningrum, 2022; Salma et al., 2024). Because low-activity radioactive waste provides a larger volume portion compared to high-activity radioactive waste such as the type of Radioactive Waste that is widely received by DPFK-BRIN in the form of liquid waste (low level), semi-liquid, organic, non-compactable and non-combustible waste. The important radionuclide to be studied in this study is Cesium-137 because most types of waste in IS 1 and 2 contain Cesium-137 radionuclides (Muziyawati & Purnama, 2017). Cesium-137 is a radionuclide element that is easily absorbed by materials in the soil ((Koarashi et al., 2019) and the Cs cation is also Group IA which has the property of being completely soluble in water so that if this ion is absorbed by groundwater and consumed by the surrounding community it can increase the risk to public health (Rauwel & Rauwel, 2019).

Bentonite deposits in Indonesia are spread across the islands of Java, Sumatra, parts of Kalimantan and Sulawesi with reserves estimated at more than 380 million tons, and generally consist of calcium (Ca-bentonite). According to data from the Ministry of Mining and Energy, Bentonite found in West Kalimantan has a variety of minerals in a wide distribution because in this area there is a very wide distribution of granite and is also supported by a tropical climate that greatly helps in the formation of other clay minerals (Soleh, 1995). The existence of abundant clay in this region can provide advantages in creating an effective retaining layer, so it is expected to minimize the risk of leakage and provide a safe environment for the storage.

Therefore, research on the use of clay soil needs to be conducted regarding the hypothesis of the influence of the density of artificial barrier materials as a potential containment of disposal facilities for nuclear waste repositories (Di Pietro et al., 2019; Alzamel, 2022; Li et al., 2025; Jalal et al., 2021). This safety function will be identified using the analysis method of the Cs-137 diffusion rate coefficient (Da, m2/s) in variations in clay soil density. Increasing clay soil density will reduce pore dimensions and the diffusion capacity of metal ions/radionuclides as well as nutrients for microbes that contribute to the degradation of disposal facility construction (Di Pietro et al., 2019). The Da value varies depending on the experimental medium and diffxusion time used, that low Da conditions in the unsaturated zone can control the possibility of radionuclide spread from the disposal facility to saturated areas or aquifers (Setiawan & Ekaningrum, 2019; Zhang et l., 2025; Martynov & Zakharova, 2024). A quantitative approach

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to the variation in density in clay soil and kaolin density at the disposal site hypothesizes that the density of the artificial barrier material (clay soil) and the natural kaolin barrier will be useful as a barrier function for the transport of Cs-137 radionuclides so that they do not reach the aquifer zone so that Cs-137 will not go to the residents' wells (hypothetical wells 100 m from NSD) for consumption for up to hundreds of years ± 230 years (Ekaningrum, 2022).

Based on the results of this study, the authors intend to conduct in-depth research related to the diffusion ability of Cs-137 to migrate through the components of the filling material (buffer) & confining material (backfill) in the radioactive waste disposal system (Rao et al., 2022; Shri et al., 2022). This study uses clay soil from West Kalimantan and uses simulated groundwater containing cations Na, K, Ca, Mg and Fe and radioactive tracer Cesium-137 because previous studies have not used radioactive materials as tracers (Sastrowardoyo et al., 2000) then uses groundwater as a saturation medium (Setiawan & Ekaningrum, 2019; Ekaningrum, 2022) and uses bentonite from the Tasikmalaya area (Salma, 2023).

By considering the variation of kaolin characteristics, such as differences in water content, in each different location, it can cause the possibility of differences in the diffusion rate of Cs-137. Therefore, the author intends to conduct a study of the effect of metal ions in groundwater taken from the Serpong Nuclear Area on the diffusion rate coefficient of Cs-137 radionuclides (Da). The data obtained will be used as a basis for analyzing the scenario of the Cs-137 migration path reaching the aquifer and then heading to the residents' wells using the RESRAD Offsite software. Well water is assumed to be consumed by the community around the disposal facility and the RESRAD Offsite software is also used to assess the impact of radioactive releases from the repository to the environment and population in the form of estimates of effective doses to critical groups. The results of this study are expected to add insight into the safety assessment program for the construction of radioactive waste disposal facilities within the framework of developing the disposal site of the Serpong Nuclear Area for Near Surface Disposal facilities.

Methods

The current study was planned as a controlled laboratory experiment and an attempt to explain, in a realistic setting environment, the behavior of the Cesium-137 when subjected to the natural barrier materials when subjected to ground-water saturated conditions. The whole methodological programmed the premise that a sound scientific design should strive to imitate nature in as much as possible as long as it can control such crucial factors. Therefore, instead of using synthetic material the research used locally available clay and kaolin in West Kalimantan which are locally abundant materials that have developed through a process of geological and climatic conditions. This option was based on practical and conceptual factors the former being the ease with which the proposed option can be adopted in future waste-management plans through the use of indigenous materials and the latter being how the diffusion science is incorporated into the larger environmental dimension of the developing nuclear infrastructure in Indonesia.

The specimen preparation was conducted following a methodical and careful procedure that put more emphasis on uniformity without losing the inherent characteristics of the specimens. The samples were at first air-dried to ensure the structure was intact, then ground and sieved to obtain a desired particle size distribution. A sieve with sixty meshes was used so that every grain was refined to a similar size, allowing it to be compared in a controlled manner without altering the natural texture of the soil. The samples were then compacted to 3 levels of density that included 1.2, 1.3 and 1.4 -1 g cm that were representative of the levels of compaction that is expected in the engineered barriers. Each compaction exercise was done accurately, so that the obtained specimens were homogeneous without subjecting them to an excessive modification of their pore structure. This strict training was aimed at balancing between experimental manipulation and self-imitation.

The experimental system was designed with a stainless -steel diffusion column, which is a vertical cross-section of a barrier containing. The design of the system was focused on the integrity and reproducibility. All the elements, such as the column sealing mechanism, the vacuum desiccator, and so on, were carefully assembled, excluding the possibility of leaks or uneven pressure that could negatively affect the diffusion process. Assistive devices like an analytical balance, oven and a high purity germanium detector among others were used not only as tools but also as extensions of precision in each case leading to a more detailed comprehension of Cs-137 migration through mineral matrices with time. Here, the laboratory was an artificial environment, which scaled geological time to a measurable scale.

An exhaustive characterization phase was done before diffusion testing to identify the mineralogical and chemical identities of the specimens. The logic behind this move was simple but deep and that is; the dynamics of a radionuclide is inherently connected to the structure and chemistry of its host media. The Inductively Coupled PlasmaOptical Emission Spectroscopy was thus used to measure key metallic elements that are known to affect the ion exchange processes, which are iron, aluminum, potassium, and sodium. X-ray Fluorescence and X-ray Diffraction analyses revealed the predominant mineral phases and crystal structures proving the existence of the such main building blocks as kaolinite, illite, and smectite. A combination of these methods of analysis allowed making a transition between the simple description of composition and the knowledge about the way mineral composition determines the potential of diffusion.

The main aim of the research was to measure the vertical Cs137 migration using saturated compacted samples. All the specimens were wetted with groundwater found in the Serpong Nuclear Area; the natural ionic composition of this water that comprises of Na +, K +, Ca +, Mg + and Fe + was considered necessary to replicate the conditions of diffusion processes that occur in the environment. After the completion of saturation, Cs 137 solution was deposited on the top of each column to start diffusion process. The independent variables were varied in a systematic manner (two, four and six weeks of diffusion), and the bulk density of the compacted matrix. During the experiment, temperature and humidity were strictly controlled, hence ruling out the possibility of the experiment to affect the rate of diffusion observed.

After every diffusion period, the columns were cut into centimetre divisions using sharp and precise methods of dissection. A depth profile of Cs-137 activity in each slice was measured using a high purity germanium detector to measure gamma activity. Based on this distribution, the diffusion coefficient was determined using the first law of Fick. Instead of looking at the calculation as a purely numeric one, the researchers used the coefficient as a measure of the physical mechanics of Cs -137 migration, i.e. between regions of high and low concentration through the mineral pore space, which are modulated by the matrix density and the elapsed time. This analysis method was used to convert abstract numerical measures to tangible environmental meanings in explaining the influence of diverse soil structure on the transfer of radionuclides in the context of containment systems.

The diffusion coefficients obtained in the laboratory were included in the RESRAD off-site to extrapolate results to actual field situations. This step allowed the adoption of empirical observation to predictive modelling, and modeled Cs 137 migration out of a near-surface disposal facility to a hypothetical well position 100m downstream. The obstacle effected by the thickness of a kaolin barrier ranging between 0.6m and 0.0 was measured through the thickness of a kaolin barrier to determine the effect of various protective arrangements on time-varying profiles and intensity of radioactive release in the immediate populations. The exposure pathways like the vegetation, livestock, dairy and potable water were modeled to address the major pathways through which the radionuclides may enter the human systems.

The simulations used inventory data of the 2023 DPFK -BRIN records, thus ensuring that the real-life depiction of the up-to-date levels of Cs -137 activity under management in Indonesia are represented. Inclusion of site specific parameters like bulk density of the soil, hydrological regimes and radioactive decay constants, allowed the model to represent a plausible long term containment performance scenario. The resultant time-dose curves not only were able to demonstrate the dynamics of diffusion of Cs-137, but also were able to demonstrate the possibility of engineered barriers to extend the protective measure well beyond centennial time-scale, ultimately to levels well lower than the general population protection threshold of one millisievert per year.

Lastly, the coefficients of diffusion were compared to the values available in the domestic and international literature. This comparative study was an external confirmation of the existing results and showed that the diffusion rates of West Kalimantan clay and kaolin had to do with the usual values of the world in terms of high-quality studies. Furthermore, these consistencies of findings indicated the local applicability of findings, implying that local materials would have similar barrier properties as those of the internationally standardized properties, hence the possibility to design safe, locally-based nuclear waste containment systems in Indonesia.

Results and Discussion

Sample Characterization Using ICP-OES

Clay and kaolin samples were analyzed using ICP-OES from the Advanced Chemistry Characterization Laboratory to identify the metal elements present. The results of the ICP-OES analysis are shown in Table 1.

Table 1. Sample Analysis Results Using ICP-OES

Metal Element	**Contents on (µg/g)**	
	Clay Soil	**Kaolin**
Al	18040.84	18862.10
Ca	*signed	*signed
Cu	20.56	10.48
Fe	6796.95	883.42
K	5060.11	790.26
Mg	486.76	135.08
M N	*signed	25.57
Na	70.83	90.41
Sr	7.85	5.91

Note ( ) : The sample was not read because it was below the standard detection limit of 10 ppb.*

From the table above, it is known that the kaolin sample contains a fairly high Alumina (Al) metal, and both samples contain Copper (Cu), Potassium (K), Magnesium (Mg), Sodium (Na), and Strontium (Sr) metals. Meanwhile, the Manganese (Mn) content is only found in the clay soil sample and both samples do not contain Calcium (Ca). This shows that the West

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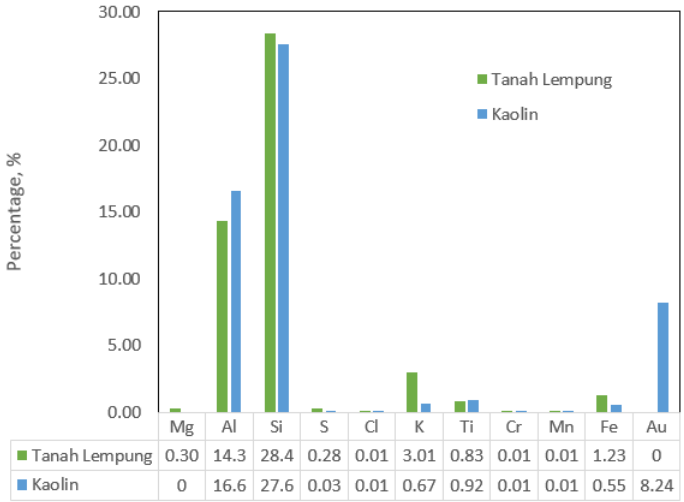
Kalimantan clay soil is proven to be a West Kalimantan clay soil deposit in Indonesia classified as a type of Na-swelling clay (Sudrajat, 1997).

Sample Characterization Using XRF

One method that can be used to analyze the elemental content of metallic minerals is the *X-Ray Fluorescence* (XRF) method. XRF is a tool used to determine the elemental content and its percentage in a material. The use of the *X-Ray Fluorescence method* in this study is based on the consideration that this technique has a detection limit of up to ppm (*parts per million*). The test results using XRF are shown in Figure 2.



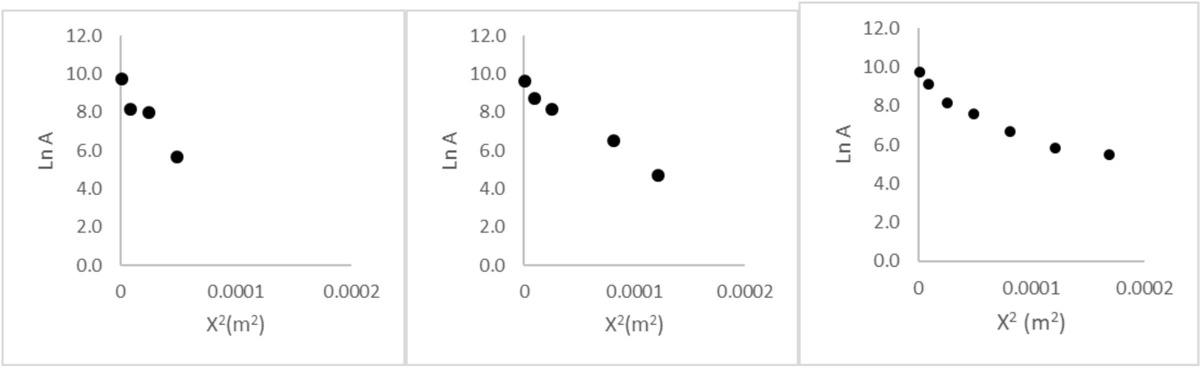
	Mg	Al	Si	S	Cl	K	Ti	Cr	Mn	Fe	Au
🟩 Tanah Lempung	0.30	14.3	28.4	0.28	0.01	3.01	0.83	0.01	0.01	1.23	0
🟦 Kaolin	0	16.6	27.6	0.03	0.01	0.67	0.92	0.01	0.01	0.55	8.24

Figure 1. Characterization of Clay and Kaolin Materials Using XRF

The analysis above shows that silica (Si) is the primary constituent of both materials. The kaolin sample contains higher levels of alumina (Al) and gold (Au) than the clay sample. The clay sample, on the other hand, contains high levels of alumina (Al) and potassium (K), thus aligning with the ICP results obtained in this study.

Da Value in Sample Effect of Time Variation

The samples tested consisted of clay and kaolin soil, which were used to observe variations in the effect of time on test results. Testing was carried out with varying times of 2, 4, and 6 weeks and a density of 1.4 g/cm ^{3}.



a b c

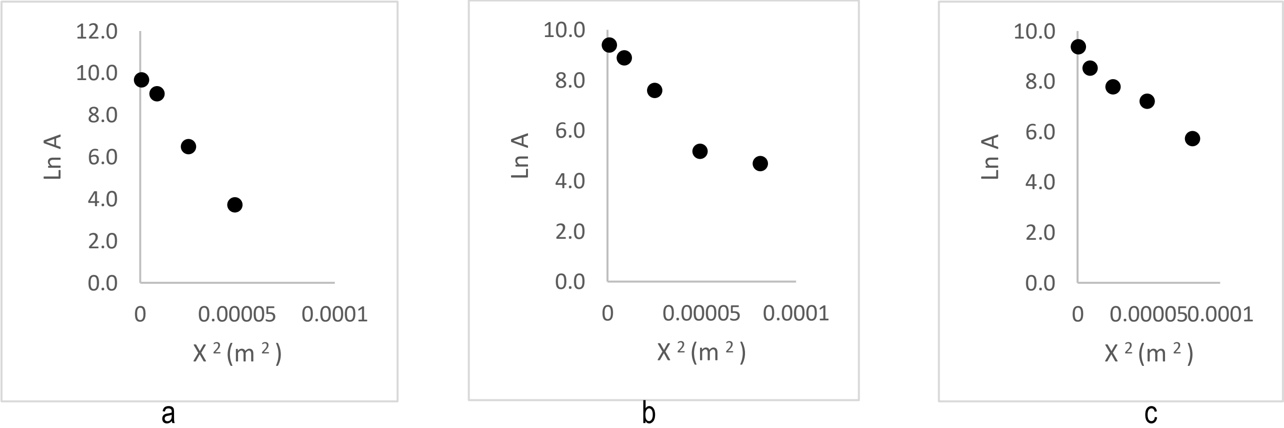
Figure 3. Cs-137 distribution graph in the diffusion column containing Kaolin samples at different times: (a) 2 weeks, (b) 4 weeks, (c) 6 weeks, with a density of 1.4 g/cm³.

With the obtained graph equation, the value of D $_a$ (m ^{2} .s $^{-1}$) can be calculated using the formula a = value $-\frac{1}{4Dt}$obtained for each time variation displayed in Figure 3. The calculation value is obtained like this.

Table 2Graph equation and D value of Kaolin samples with time variation

Time (week)	**Y = ax + b**	**D $_a$ (m ^{2} .s $^{-1}$)**
2	Y = -75056x + 9.4751	2.75 x 10 $^{-12}$
4	Y = -37322x + 9.3144	2,77 x 10^{-12}
6	Y = -24678x + 9,1132	2,79 x 10^{-12}

Initially, the concentration of Cs-137 according to Figure 3 is more dominated in the surface area of the sample because the surface is dripped by Cesium radioniclide and over time the diffusion trace of Cs-137 is getting wider so it can be seen that Cs-137 gradually diffuses into deeper parts of the sample at a longer diffusion time with a constant speed, Because the value of the diffusion coefficient in the system created in this study also remains constant. Another factor that affects the value of the constant diffusion coefficient over time is the natural nature of Cs-137 which has a fairly long half-life of around 30.23 years can affect the stable concentration of Cs-137 over time because its decay rate is relatively slow. The impact is that the dependence on time becomes insignificant in the short term or after several years. In addition, Cs-137 is an element that is easily dissolved and absorbed on surface particles so it is likely not too susceptible to changes in chemical properties and surface properties over time that affect the stability of the diffusion coefficient. The next sample is clay soil saturated using simulated groundwater from West Kalimantan. Testing was carried out with time variations for 2, 4, and 6 weeks.



a b c

Figure 4. Cs-137 distribution in the diffusion column with Kaolin samples at 1.4 g/cm³ for (a) 2, (b) 4, and (c) 6 weeks.

The calculated values for each time variation are shown in Figure 4, the resulting D$_a$ values are shown in this table.

Table 3Graph equation and D$_a$ value of clay soil samples with time variations

Time (week)	**Y = ax + b**	**D$_a$ (m ^{2} .s $^{-1}$)**
2	Y = -127267x + 9.8693	1.62 x 10 $^{-12}$
4	Y = -63243x + 9.229	1.63 x 10 $^{-12}$
6	Y = -41702x + 9.0814	1.65 x 10 $^{-12}$

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It can be seen in the graph that the activity is more dominantly detected near the surface of the clay soil and over time the diffusion trace of Cs-137 increasingly diffuses into deeper parts of the soil at a longer diffusion time with a constant speed, this occurs because the value of the diffusion coefficient that occurs in this system is constant. Another thing that affects the value of the constant diffusion coefficient over time is the natural nature of Cs-137 which has a half-life of 30.23 years can affect the magnitude of the stable Cs-137 concentration over time because the decay rate is slow because this experiment only uses the longest time variation of 6 weeks. The impact that occurs shows that the dependence on time is not significant both in the short term and after several years. In addition, Cs-137 is easily dissolved and absorbed by other surface particles so it is not very susceptible to changes in the chemical and physical properties of the soil over time.

The stability of the Cs-137 diffusion coefficient over time is important for predicting the movement of radioactive isotopes in the environment. Based on existing data, clay soil exhibits a slower diffusion coefficient than kaolin. This indicates that clay soil is more effective in inhibiting the movement of Cs-137, making it a better choice for potential disposal sites in time-varying experiments. Therefore, the use of clay soil as a material in disposal sites can improve environmental safety and stability from radioactive contamination.

Table 4Comparison of Da values of samples at different times

Sample	**Diffusion Coefficient ($m^2.s^{-1}$)**		
	2 weeks	**4 weeks**	**6 weeks**
Kaolin	2.75 x 10^{-12}	2.77 x 10^{-12}	2.79 x 10^{-12}
Clay Soil	1.62 x 10^{-12}	1.63 x 10^{-12}	1.65 x 10^{-12}

Da Value in Samples Influence of Density Variation

In this study, clay and kaolin soil samples were used with density variations of 1.2; 1.3; 1.4 gr/cm ^{3} with a time of 6 weeks.

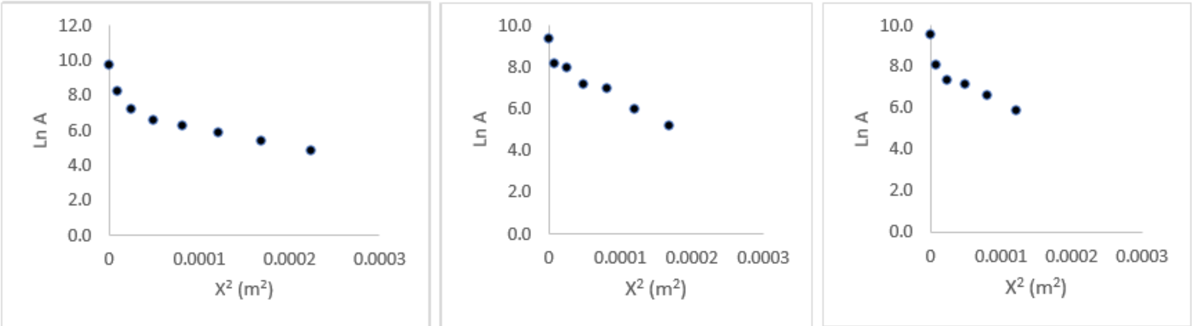

Figure 2Graph D_a Cs-137 in a diffusion column containing Kaolin samples with varying densities (a) 1.2 (b) 1.3 (c) 1.4 g/cm ^{3}

The results obtained from calculating the Da value on the kaolin sample are as follows.

Table 5. Graph equation and D value of kaolin samples with density variations

Density	**Y = ax + b**	**D_a ($m^2.s^{-1}$)**
1.2	Y = -17411x + 8.2358	3.96 x 10^{-12}
1.3	Y = -21906x + 8.665	3.14 x 10^{-12}
1.4	Y = -24678x + 8.5845	2.79 x 10^{-12}

It can be seen that the effect of density variations on the Da value with a diffusion time of 6 weeks is that the diffusion coefficient value decreases significantly with increasing density in the kaolin sample column so that the diffusion process becomes slower. This diffusion coefficient depends on several factors, including soil porosity, which is the ratio between the volume of soil cavities and the total volume of the soil. Denser soils tend to have smaller pores, which greatly affect the movement of Cs-137 in kaolin. The next sample will use clay soil with a density of 1.2; 1.3; 1.4 g/cm3 . The test will be carried out during a diffusion period lasting 6 weeks.

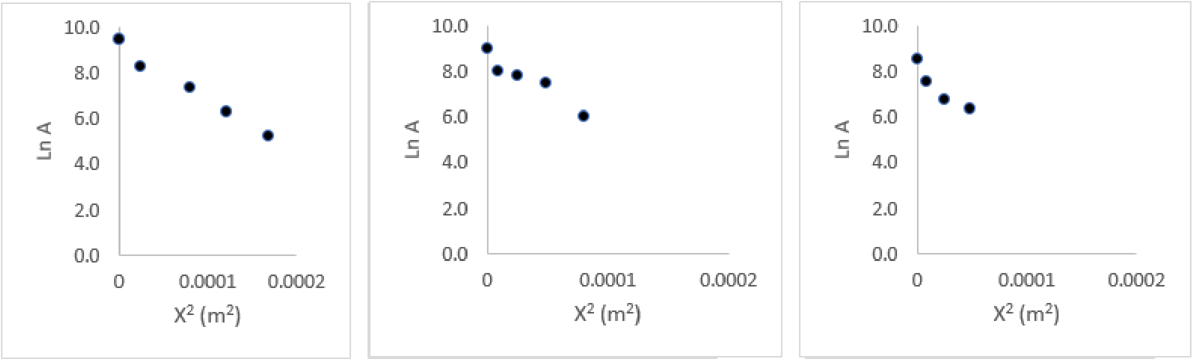

Figure 3Graph D $_a$ Cs-137 Diffusion Column Filled with Clay Soil Density Variation (a) 1.2 (b) 1.3 (c) 1.4 g/cm ^{3}

The results of the diffusion coefficient for density variations in the clay soil column are as follows.

Table 6Graph equation and D value of clay soil samples with density variations

Density	**Y = ax + b**	**D $_a$ (m ^{2} .s $^{-1}$)**
1.2	Y = -23584x + 9.212	2.9 x 10 $^{-12}$
1.3	Y = -31354x + 8.7031	2,20 x 10 $^{-12}$
1,4	Y = -41702x + 8,1803	1,65 x 10 $^{-12}$

The greater the density value, the smaller the Cs-137 diffusion coefficient value so that the diffusion process becomes slower. This diffusion coefficient depends on several factors including tortuosity that draws twists and the interconnectedness of pore spaces due to the influence of the transport process through porous media (Jayasree et al., 2021). This affects the Cs-137 diffusion coefficient, denser clay soils tend to have smaller pores and fewer cavities, thus limiting the movement of particles through them (Silva, Cardoso, & Veronese, 2022). This makes the diffusion of Cs-137 through denser media slower than soil or less dense media. Then another factor is the mineral content in clay soil with groundwater saturation, groundwater containing many ions can interact with kaolinite minerals (Sari et al., 2016) and can increase the diffusion coefficient. Thus, saturation of clay soil with groundwater can increase the adsorption capacity of clay soil to ions. The D $_{a\ value}$ decreases as the density of the medium increases. This means that the rate of particle diffusion through denser media is slower than through less dense media. Denser media have more particles resulting in more collisions and obstacles for the diffusing particles to overcome.

Table 7. Comparison of D a Values of Samples in Density Variations

Sample	**Diffusion Coefficient (m²/s)**	**1.2 g/cm³**	**1.3 g/cm³**	**1.4 g/cm³**
Kaolin		4×10^{-12}	3.1×10^{-12}	2.8×10^{-12}
Clay Soil		2.9×10^{-12}	2.2×10^{-12}	1.7×10^{-12}

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The study used comparisons with other studies to compare clay soil from West Kalimantan with other studies to find the best material for disposal construction. Salma's study used host rock disposal soil samples with groundwater saturation in Tasikmalaya (Salma, 2023). This study also compared the results of the study with several different journals. This study used soil originating from 12 countries located in the northern hemisphere (Jagercikova, Cornu, & Bas, 2015). Then, benchmarking was carried out on the research of Sato et al. Using soil deposited in the environment in Fukushima Prefecture and its surroundings with unsaturated conditions because it is located near the surface layer of the soil (Sato & Hirota, 2019).

Table 7Benchmarking of Clay and Kaolin Soil from various studies

D_a ($m^2.s^{-1}$)	Material	Reference
2.2×10^{-12}	West Kalimantan Clay Soil	Research result
1.7×10^{-13}	Host rock disposal land	(Salma, 2023)
3.9×10^{-13}	Chernobyl fallout contaminated soil	(Cho, Lee, & Kang, 2001)
3.2×10^{-11}	Fukushima prefecture land	(Satoru Suzuki & Suzuki, 2012)
5×10^{-13}	Host rock disposal land	(Ekaningrum, 2022)
1.29×10^{-12}	West Kalimantan Clay Soil Water Saturation Demin	(Devi, 2024)
3.3 x 10 -12	West Kalimantan Kaolin	Research result
2.4 x 10 -12	West Kalimantan Kaolin Demin Water Saturation	(Devi, 2024)

Effect of Metal Ions

The analysis of each sample in this study produced various metal ions such as Fe, Al, and Si which were dominant. The results of this study indicate that other cations such as Na^+, Ca^+, K^+, Cu^{2+}, Mg^{2+}, Mn^{2+} and Fe^{2+} in groundwater cause changes in the diffusion coefficient value of Cs-137 in the sample when compared to the use of demineralized water. The results obtained in this study refer to table 8 which has a higher diffusion coefficient value at groundwater saturation compared to the use of demineralized water. The diffusion coefficient value of the Cs-137 cation appears to increase with the presence of other cations. Ions such as Ca, Na, K, Mg, Mn, and Fe have the ability to influence soil characteristics and modify pore structures that can affect the diffusion coefficient of Cs-137. These ions can interact with Cs-137 and in several other studies are known to affect the absorption process of Cs-137 in the soil. the presence of these cations in soil solution can vary in their effect on the diffusion coefficient (Da) of Cs-137 through the soil depending on their chemical characteristics and concentration.

Offsite Resrad Data Results

Inventory data from DPFK in 2023 for Cs-137 has a total activity of 164684.9 GBq or 1.65 x ^{1014} Bq which is one of the largest stored by DPFK with a total of 24% of the total warehouse from DPFK. There are 18 modules, each containing 675 drums, so the total is 29,300 drums weighing 466 kg, so 5.65 x 10^9 grams are obtained. The concrete shell container weighs 6.4 tons in the form of a waste package, it takes around 1296 concrete shells which results in 8.29 x 10^9 grams . Adding the concrete shell and drums, the result is 1.4 x 10^{10} grams. The input data requirements for RESRAD must be Bq / gr, so $\frac{1,65 \; x \; 10^{14} Bq}{1,4 \; x \; 10^{10} gr}$the result is 1.18x$10^4$ Bq / gr.

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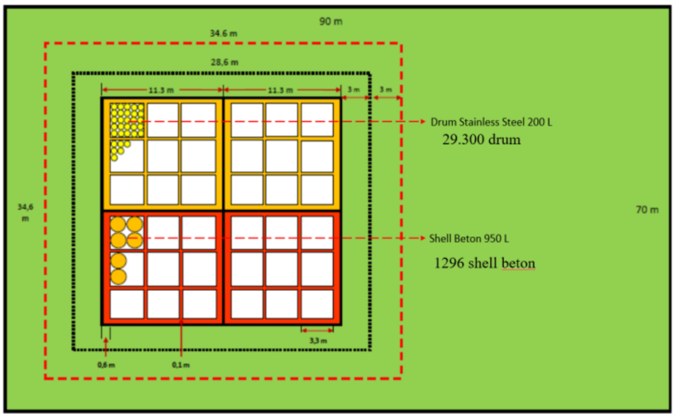

Figure 4Schematic Dimensions and Layout of Radioactive Waste at the Facility

Figure 7 shows the dimensions and layout of the radioactive waste that will be implemented in the disposal facility to ensure safe and orderly storage. This dimension data will be entered into the RESRAD Offsite input data. After all the input data is entered, it will be run immediately, then the output in the form of reports, graphs and the amount of dose received can be viewed and evaluated. Changes were made to the artificial barrier with variations in kaolin thickness, namely 0.2; 0.4; 0.6 m and without kaolin. This change can be made by clicking on the unsaturated zone hydrology and changing it in the second layer. After conducting several experiments, the maximum effective dose results from all variations in kaolin thickness were obtained as follows.

Table 8Maximum Effective Dose Values

Kaolin Thickness Variation (m)	Maximum Effective Dose (mSv/year)	The 20th Year	% of NBD Society
0.0	5.399×10^{-3}	242	0.5399%
0.2	5.075×10^{-3}	245	0.5075%
0.4	4.717×10^{-3}	248	0.4717%
0.6	4.386×10^{-3}	251	0.4386%

After this process, we can click "results" and then "deterministic graph." A graph will appear depicting year versus mSv/year. This graph makes it easier to identify the correct kaolin. Once the graphs for each kaolin thickness variation are obtained, they are combined to facilitate comparison.

According to the results shown in Figure 4.10, it can be seen that there is a decrease in the maximum effective dose along with the increase in layer thickness and the time required to reach the peak dose will be longer. The accepted Dose Limit (DLT) value for the community is 1 mSv/year, the initial variation results without kaolin are categorized as still quite small where the contribution value is very small from the community's DLT. The purpose of this safety assessment analysis without a kaolin barrier is needed to determine the impact of reducing the dose and concentration of Cs-137 received by the surrounding community.

The Offsite RESRAD feature allows users to view a graph of exposure pathways that impact the environment and predict which elements will be affected first by radionuclide contamination. In addition to the graph, there are also dose values in mSv/year for various elements that may come into direct contact with humans and the environment, as shown in Table 10.

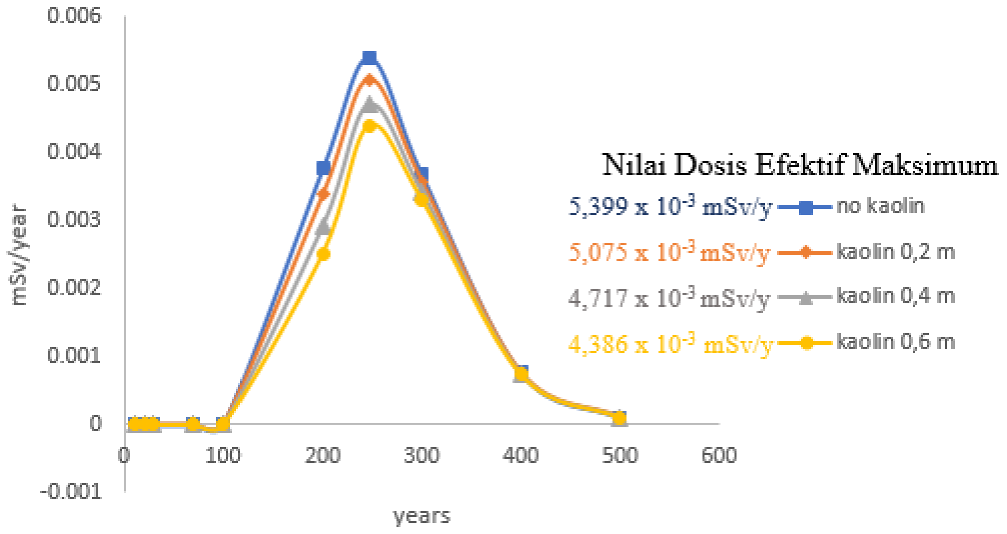

Figure 8. Graph of all Cs-137 doses in the Safety Assessment scenario for all variations

Table 9Comparison of NBD with doses at various kaolin thicknesses received along the exposure route to public consumption

Types of food	**Dose limit (mSv/year)**	**Offsite RESRAD Result Dose (mSv/year)**			
		No kaolin	**Kaolin 0.2 m**	**Kaolin 0.4 m**	**Kaolin 0.6 m**
Plant	0.15	$1,86 \times 10^{-3}$	$1,75 \times 10^{-3}$	$1,63 \times 10^{-3}$	$1,51 \times 10^{-3}$
Meat	0,02	$1,65 \times 10^{-3}$	$1,55 \times 10^{-4}$	$1,44 \times 10^{-3}$	$1,34 \times 10^{-3}$
Drinking water	>100	$1,13 \times 10^{-3}$	$1,06 \times 10^{-3}$	$9,83 \times 10^{-4}$	$9,14 \times 10^{-4}$
Milk	>100	$7,43 \times 10^{-4}$	$6,98 \times 10^{-4}$	$6,49 \times 10^{-4}$	$6,03 \times 10^{-4}$

From the RESRAD data obtained if looking at the safety aspect then the selection of 0.2 m kaolin is actually sufficient, but to create a safer feeling then the selection of 0.6 m Kaolin is the safest choice with various considerations such as the maximum dose limit value that can be withstood by disposal using this variation up to 251 years is expected to be safer to the surroundings. Based on Table 10 the greatest exposure will be received through the plant route then meat, drinking water and milk. Health effects due to radiation exposure through drinking water are related to radiation protection which is based on the assumption that every radiation exposure must involve some level of risk. Long-term exposure such as drinking water containing radionuclides over a long period of time shows evidence of an increased risk of cancer in humans if the dose is above 100 mSv (Brenner, et al., 2003).

Disposals that store Cs-137 waste will eventually disintegrate over time, but this takes a very long time. During this period, the activity of Cs-137 decreases over time because the half-life of Cs-137 is ± 30 years. The activity of Cs-137 after the disposal is destroyed is estimated to be very far from the public NBD because its activity has decreased due to the half-life. Therefore, storing radioactive waste in NSD disposal with artificial Kaolin barriers is considered safe, because it ensures that the radiation risk to humans and the environment is below the NBD and is controlled.

Conclusion

The Da value does not significantly affect the time variation obtained in this study with the Cs-137 diffusion coefficient value in the range of 2.7 x10 -12 m2 /s for kaolin samples with only a very small difference of 0.02 x 10 -12 m2 /s and 1.6 x 10 -12 m2 /s in clay samples with a difference of 0.015 x 10-12 m2 / s. The Da value in density variations decreases with increasing density. This is because the rate of particle diffusion through denser media will slow down compared to less dense media. The Cs-137 Da value obtained from this study is mostly two times smaller in clay samples than in kaolin samples. This means that clay is more effective at retaining by slowing down the diffusion coefficient. The diffusion coefficient value of Cs-137 cation in groundwater saturation experiences changes where the value increases with the presence of other cations when compared to the value of the Cs-137 diffusion coefficient whose saturation uses demineralized water. This is due to competition between cations where Cs ions with groundwater metal ions have diverse characteristics that impact the diffusion ability of Cs-137. Offsite RESRAD testing for safety assessment obtained the maximum effective dose value and the consumed radiation dose, the decrease in the maximum effective dose occurs along with the increase in layer thickness and the time to peak dose will be longer. The maximum effective dose value tends to be similar, in use without kaolin the results obtained are 0.5399% of the community's NBD and will be maximum at 242 years. In the thickest variation, namely 0.6 m thick kaolin, the results obtained are 0.4386% of the community's NBD and will be maximum at 251 years.

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