Safety assessment of near surface disposal for radioactive waste in Serpong nuclear area using PRESTO software

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Abstract. The planning of the construction and operation of Near Surface Disposal (NSD) facilities for Radioactive Waste at Serpong Nuclear Area needs a safety assessment in order to provide assurance that the radioactive waste disposal system functions properly. The purpose of the safety assessment is to provide a reasonable scientific assurance that the disposal system will provide an adequate level of safety and meet the requirements to protect human health and the environment. The NSD facility is vault type with a size of 20.2 × 20.2 m with a depth of 2.6 m from the ground surface (4.43 m above the highest ground water level). The facility was designed to accommodate waste packaged in 200 l drums and 950 l concrete shells. The total capacity of the disposal will be 1350 drums and 144 concrete shells. The waste that was considered in the study contain radionuclides which are dominantly contained in the low level packaged waste and, as reference for the safety assessment, with short half-lifes (less than or equal to about 30 years), namely Co-60 and Cs-137. This study used the PRESTO software version 4.2 to calculate the migration/exposure of radionuclides from the facility into the environment as well as individual doses. The results indicate that the predicted individual doses of the population around the facility at the Serpong site still fulfill the dose limit value of the public based on BAPETEN Chairman Regulation No. 4/2013 on the Protection and Radiation Safety in the Utilization of Nuclear Energy.

1. Introduction
The planning of the construction and operation of near surface disposal (NSD) facility for low level radioactive waste needs a safety assessment. The NSD type that has been chosen was based on the suitability with the waste characteristic and the site. The purpose of the construction and operation of NSD is to dispose the accumulated low level radioactive waste that have been immobilized and packaged since 1988 at the Radioactive Waste Installation (RWI) and stored at the Interim Storage (IS) located at the Serpong Nuclear Area (SNA). The NSD facility in SNA is dedicated also for the Demonstration Plant of Radioactive Waste Disposal (DP-RWD) to demonstrate the safety and durability of the disposal system [1, 2].

In order to provide assurance that radioactive waste disposal system is functioning properly, it is necessary to predict the individual dose as a part of safety assessment. Safety assessment is an iterative procedure to evaluate the performance of the disposal system and its potential impact on human health and the environment [3]. The purpose of safety assessment is to provide a reasonable scientific assurance that disposal system will provide an adequate level of safety and meet the requirements to protect human
health and the environment. In the Article 23 of BAPETEN Chairman Regulation No. 4/2013, it is mentioned that dose constraint value for public is 1 mSv/year [4].

The candidate of NSD facility is located in the SNA, PUSPIPTEK Area, Serpong, Banten (Figure 1). The site characterization has been performed since 2010 with engineering geology, hydrogeology, and environmental geology investigations [5].

Figure 1. Map of NSD location at Serpong Nuclear Area, PUSPIPTEK, Serpong, Banten [5].

A safety assessment of demonstration plant for radioactive waste disposal (DP-RWD) has been performed in 2012 with different data of waste, conceptual design and site [6], so that the safety assessment must be updated with new data of waste, detail design (ready to be constructed) and some updated site data.

Assessment of radionuclide release scenario to groundwater (well water) and surface water (river) from the demonstration plant of near surface disposal for low level radioactive waste at SNA had been performed [7]. The result of the assessment showed that concentration of radionuclide still fulfilled the BAPETEN Chairman Regulation No. 7/2013 on Boundary Value of Environmental Radioactivity, which set the maximum concentration of radionuclide in water body at $10^2$ Bq/m$^3$ to $10^5$ Bq/m$^3$ [8]. Based on the results of calculation, the maximum concentration of radionuclide in well water was $10^{-10}$ Bq/m$^3$ to $10^0$ Bq/m$^3$ and in surface water about $10^{-13}$ Bq/m$^3$ to $10^{-1}$ Bq/m$^3$.

As a comparison, in India, a probabilistic safety assessment model for assessing the performance of near surface disposal facilities for low-level radioactive waste had been performed [9]. The annual effective doses derived from the uncertainty analysis fall in a log normal distribution with a geometric mean of $3.6\times10^{-2} \pm 3.9$ mSv and the most probable annual effective dose to a member of the critical group works out to be $2.8\times10^{-4}$ mSv.

Korea also has developed a safety assessment of near surface disposal facilities for LILW using SAGE and VR-KHNP computer code [10]. Through the comparison of radionuclide release rates at near- and far-field, two computer codes show good agreement.

Still in Korea, post-closure safety assessment was carried out for DSRSs generated from 1991 to 2014 in Korea in order to ensure long-term safety of near surface disposal facilities [11]. Two kinds of disposal options were considered, i.e., engineered vault type disposal facility and rock-cavern type disposal facility. Assessment endpoint was individual dose to the member of critical group, which was modeled by GoldSim, which has been widely used as probabilistic risk analysis software based on Monte Carlo simulation in the area of safety assessment of radioactive waste facilities. In normal groundwater
scenario, the maximum exposure dose was extremely low, approximately $1 \times 10^{-7}$ mSv/yr, for both disposal options and satisfied the regulatory limit of 0.1 mSv/yr.

2. Overview of the design of proposed near surface disposal facility
The NSD facility is vault type in $20.2 \times 20.2$ m size with a depth of 2.6 m from the ground surface (4.43 m above the highest ground water level). The facility was designed to accommodate waste packaged in 200 l drum and 950 l concrete shell. The capacity of the disposal will be 1350 drums and 144 concrete shells [2]. The first emplacement will be started at compartment 1D and 1S for about 675 drums and 72 shells of radioactive waste that would be accumulated in about 25 years later. The general layout of the proposed facility can be seen at Figure 2.

The radionuclides contained in the waste that was considered in the study were radionuclides which dominantly contain in the packaged waste and as reference for the safety assessment with short half-life of less than or equal to about 30 years, namely Co-60 and Cs-137 [12]. The assumption based on the calculation of total activity of Co-60 of 301 032 Bq and Cs-137 of 5 857 920 Bq.

![Figure 2. Layout design of proposed NSD [2].](image)

3. Method
The safety assessment of NSD facility in Serpong Nuclear Area uses Prediction of Radiation Effects from Shallow Trench Operation – Environmental Protection Agency – Critical Population Group/General Population (PRESTO-EPA-CPG/POP) software version 4.2, issued by the U.S. Environmental Protection Agency (US-EPA) [13]. PRESTO software version 4.2 is divided into two PRESTO-EPA-CPG and PRESTO-EPA-POP. PRESTO-EPA-CPG model is designed to calculate the maximum individual dose to the on-site population and critical population group of off-site population. PRESTO-EPA-POP model is designed to calculate the cumulative number of fatal cancer effects and serious genetic effects on the population at the site, off-site residents, and the general population.

Scenarios selected in this safety assessment is the scenario of the migration of radionuclides through the groundwater pathway. In general, hydrologic transport is the main cause of population exposed by radioactivity emanating from the disposal. The main sources of water, which led to the leaching of radionuclides from contaminants matrix, is precipitation. Precipitation water at the site will be infiltrated into the soil, flows over the surface of the ground, or evaporated into the atmosphere.

Transport of radionuclides from the site may occur due to water infiltration or runoff. A dynamic model, which calculates evaporative water loss and water transport based on the dynamic equations, is used to calculate the rate of infiltration [13]. The water that infiltrated into the zone of contamination
will leach the radionuclide of the zone. Contaminated water that flows as runoff or infiltrate into the site as a percolation flow, eventually will enter the aquifer.

Radionuclides that eventually reach the aquifer generally will be transported at speeds lower than or equal to the speed of water flow in the aquifer. Retardation as the interaction of radionuclides with the solid media in the aquifer, known as the effect of sorption (uptake). When radionuclides are transported in the aquifer to the wells water, it will be consumed by residents in the site and/or off-site area through the drinking water, irrigation, and livestock feed. Radionuclide remaining in the aquifer is considered transported further and causing a general population health impacts on downstream areas.

Water contaminated at the site would be accumulated if the infiltration rate exceeds the ex-filtration rate out of the contaminated zone. When the volume of water that accumulates in the waste exceeds the cavity / total porosity, contaminated water will overflow to the land surface. Radionuclides in the contaminated water would then mix with surface water flow and subsequently to the flow (river) nearby. Potentially, contaminated water will be consumed by local residents and residents who live downstream through drinking water, irrigation, livestock feed and aquaculture.

3.1. Mathematical models for calculating radiological dose
Many equations are used as mathematical models for calculating the parameters of safety, but due to space limitations, only a simple formula to calculate the annual dose received by the population will be presented. The annual dose of individuals at a site k for the organ l, nuclide i, and an exposure pathway j is expressed as [13]:

\[ D_{ijl}(k) = \frac{K_j E_{ij}(k) \cdot DF_{ij}}{P(k)} \] (1)

\( K_j \) : numerical factor introduced by units Eij (k),
\( E_{ij}(k) \) : exposure of radionuclide i in the exposure path j,
\( DF_{ij} \) : dose rate factor of radionuclide i exposure pathways j and organ l, and
\( P(K) \) : population on location k.

3.2. Input data
The input data used for the PRESTO software version 4.2 is the primary data obtained from field investigation on engineering geology and hydrogeology of candidate site for NSD facility at Serpong Nuclear Area [4, 14-16], climate data [17], secondary data and some assumption data about site [6], conceptual design of the NSD facility [2], and data of radioactive waste that will be disposed of [12]. The input data can be seen in Table 1, Table 2, Table 3, Table 4, Table 5, and Table 6.

| No | Aspect | Parameter | Unit | Data |
|----|--------|-----------|------|------|
| 1  | Basement | Fraction of Rn-222 emanation for contaminated soil | -- | 0.3 |
|    |  | Depth of underground basement | m | 3 |
|    |  | Thickness of basement floor concrete | m | 0.2 |
|    |  | Porosity of floor concrete | -- | 0.18 |
|    |  | Length of basement side | m | 3 |
|    |  | Negative indoor house pressure | Pa | 2.4 |
|    |  | Perimeter shrinkage crack width | m | 0.001 |
|    |  | Ventilation rate of basement | change/s | 2.78×10^-4 |
|    |  | Square of basement floor | m² | 9 |
|    |  | Basement occupancy fraction | -- | 0.6 |
|    |  | Outdoor, onsite occupancy fraction | -- | 0.2 |
The sorption capacity of soil at NSD site to certain radionuclide is relatively high. Evidence for this phenomenon was provided by the research that found that the Kd value of the soil to strontium in the range of 1600-2350 ml/g [18] and to cesium in 1400-1900 ml/g [19].

**Table 2.** Data of NSD facility.

| No | Aspect   | Parameter                  | Unit  | Data  |
|----|----------|----------------------------|-------|-------|
| 1  | Cover    | Thickness                  | m     | 1.2   |
|    |          | Density                    | g/cm³ | 1.5   |
|    |          | Porosity                   | --    | 0.38  |
|    |          | Permeability                | m/hr  | 0.02  |
|    |          | Average slope               | m/m   | 0.02  |
|    |          | Average length slope        | m     | 100   |
|    |          | Pellicular water deficit    | m     | 0.01  |
|    |          | Gravity water deficit       | m     | 3.1   |
|    |          | Pellicular water            | --    | 0.47  |
|    |          | Gravity water               | --    | 0.01  |
|    |          | Diffusivity                 | m/hr  | 0.00014 |
|    |          | Hydraulic conductivity     | m/hr  | 1.1x10⁻⁶ |
| 2  | Waste    | Thickness                  | m     | 2.6   |
|    |          | Density                    | g/cm³ | 2.36  |
|    |          | Porosity                   | --    | 0.4   |
|    |          | Permeability                | m/hr  | 2.2   |
|    |          | Absorbing waste            | --    | 0.1   |
|    |          | Activated metals           | --    | 0.1   |
|    |          | Solidified waste           | --    | 0.1   |
|    |          | Containerized fraction     | --    | 0   |
| 3  | Vertical zone |Thickness            | m     | 4.43  |
|    |          | Density                    | g/cm³ | 1.48  |
|    |          | Porosity                   | --    | 0.3797|
|    |          | Permeability                | m/hr  | 5.967 |

**Table 3.** Atmospheric data.

| No | Aspect              | Parameter                                                                 | Unit       | Data     |
|----|---------------------|---------------------------------------------------------------------------|------------|----------|
| 1  | Atmosphere         | Site environment              | humid south |          |
|    |                     | Deposition velocity           | m/s        | 0.01     |
|    |                     | Gravitational settling velocity | m/s         | 0.01     |
|    |                     | Onsite dust loading from mechanical disturbance | g/m³        | 5x10⁻⁵  |
|    |                     | Fraction of time the wind blows in direction of interest | --        | 0.31     |
|    |                     | Annual average windspeed in direction of interest | m/s        | 5.14444  |
|    |                     | Resuspension equation parameter | --        | 10x10⁻⁶  |
|    |                     | Stability category indicator | --        | D        |
|    |                     | Pasquill-Gifford atmospheric stability class formation | --        | 0.543    |
|    |                     | Height of the inversion layer | m         | 500      |
|    |                     | Hosker’s roughness parameter | m         | 0.01     |
|    |                     | Atmospheric transport parameter | --      | 5.186x10⁻⁸ |
Table 4. Site characteristic data.

| No | Aspect | Parameter                   | Unit        | Data      |
|----|--------|-----------------------------|-------------|-----------|
| 1  | Hydrology | Annual precipitation     | m           | 1.752     |
|    |         | Annual stream flowrate     | m$^3$/year  | 7,136,597 |
|    |         | Distance to nearest well   | m           | 50        |
|    |         | Distance to nearest stream | m           | 175       |
| 2  | Aquifer | Thickness                  | m           | 10        |
|    |         | Density                    | g/cm$^3$    | 1.48      |
|    |         | Porosity                   | --          | 0.3747    |
|    |         | Permeability                | m/hr        | 1x10$^{-7}$|
|    |         | Fraction of water saturation| --         | 0         |
|    |         | Groundwater velocity       | m/yr        | 0.66      |
|    |         | Angle of dispersion        | radian      | 0.3       |
|    |         | Allow aquifer to stream flow| m         | yes       |
| 3  | Erosion | Rain factor                | R/year      | 15.1548   |
|    |         | Soil erodibility factor    | ton/acre    | 0.007     |
|    |         | Plant management factor    | --          | 0.0175    |
|    |         | Erosion control application factor| --     | 0.6       |
|    |         | Sediment delivery ratio factor| --    | 1         |
|    |         | Slope steepness-length factor| --     | 0.56      |
|    |         | Fraction of residual saturation | --     | 0.17      |
|    |         | Fraction of total annual precipitation for infiltration calculation| --     | 0.334     |
|    |         | Top soil layer precipitation run-off fraction| -- | 0.005     |
|    |         | Bottom soil layer precipitation run-off fraction| -- | 0.1       |
|    |         | Active depth of soil in surface-contaminated region| --     | 0.1       |
|    |         | Width of the contaminated site measured perpendicular to groundwater flow | -- | 28.6    |
|    |         | Length of the contaminated site parallel to groundwater flow | -- | 28.6    |

Table 5. Human uptake data.

| No | Parameter                      | Unit | Data |
|----|--------------------------------|------|------|
| 1  | Human uptake to vegetables     | kg/yr| 14   |
| 2  | Human uptake to harvest product| kg/yr| 102.4|
| 3  | Human uptake to cow milk       | L/yr | 73   |
| 4  | Human uptake to goat milk      | L/yr | 6    |
| 5  | Human uptake to drinking water | L/yr | 73   |
| 6  | Human uptake to meat           | kg/yr| 3    |
| 7  | Human uptake to fish           | kg/yr| 3    |
| 8  | Human uptake to soil           | kg/yr| 1    |
| 9  | Human inhalation rate          | m$^3$/yr| 7300 |
Table 6. Plants and animals data.

| No | Aspect                        | Parameter                     | Unit | Data  |
|----|-------------------------------|-------------------------------|------|-------|
| 1  | Agriculture productivity      | Grass                         | kg/m² | 0.0015|
| 2  | Daily water consumption       | Dairy cows                    | L/d  | 0     |
|    |                               | Dairy goat                    | L/d  | 0     |
|    |                               | Beef cattle                   | L/d  | 0     |
| 3  | Time between harvest to       | Grass                         | hour | 12    |
|    | consumption                   | Stored feed                   | hour | 0     |
|    |                               | Leaf                          | hour | 0     |
|    |                               | Fruit                         | hour | 12    |
| 4  | Exposure time in the          | Grass                         | hour | 1401.6|
|    | contaminated air              | Harvest product               | hour | 1401.6|
| 5  | Food consumption              | Dairy goat                    | kg/d | 0     |
|    |                               | Beef cattle                   | kg/d | 0     |
|    |                               | Transport time from animal    | hr   | 48    |
|    |                               | feed to human receptor        |      |       |
|    |                               | Time from animal slaughter    | hr   | 480   |
|    |                               | to human consumption         |      |       |
|    |                               | Weathering removal decay     | hr⁻¹ | 0.0021|
|    |                               | constant                     |      |       |
|    |                               | C-14 fractional equilibrium  | --   | 1     |
|    |                               | value                        |      |       |
|    |                               | Absolute saturation of air    | gr/m³| 18.172|
|    |                               | Root depth                    | m    | 0.75  |
|    |                               | Irrigation flow rate          | L/m-hr | 2880 |
|    |                               | Infiltration fraction of     | --   | 0.5   |
|    |                               | precipitation                |      |       |
|    |                               | Fraction of year that crops  | --   | 0.4   |
|    |                               | are irrigated                |      |       |
|    |                               | Fraction of year animals     | --   | 0.25  |
|    |                               | graze on the pasture grass   |      |       |
|    |                               | Fraction of animal’s daily   | --   | 0.25  |
|    |                               | feed that is fresh grass     |      |       |

4. Results and discussion

From the calculation results with the PRESTO 4.2 software obtained some output as can be seen in Figure 3, Figure 4, Figure 5, Figure 6, and Figure 7.

At Figure 3 it can be seen that the radionuclide in well water consisted of Co-60 only. The concentration of Co-60 in well water is about 4.0×10¹⁰ Bq/m³ in year 200 after closure and the concentration tend to decrease until about 3.0×10¹⁵ Bq/m³ in year 300 after closure of the NSD. If compared to the BAPETEN Chairman Regulation No. 7/2013 on Boundary Value of Environmental Radioactivity, which the maximum concentration of radionuclide in water body is 10² Bq/m³ to 10⁵ Bq/m³, so the concentration of radionuclide in well water in range between 10¹⁵ Bq/m³ to 10¹⁰ Bq/m³ are still far below the boundary value.

Figures 4 and 5 show the concentration of radionuclide in surface water is consisted of Co-60 and Cs-137. The maximum concentration of Co-60 in surface water is about 1.52×10⁻³ Bq/m³ in the first year after closure and the concentration tend to decrease until about 9.44×10⁻₂⁶ Bq/m³ in year 401 after closure of the NSD. If compared to the BAPETEN Chairman Regulation No. 7/2013 on Boundary Value of Environmental Radioactivity, which the maximum concentration of radionuclide in water body is 10² Bq/m³ to 10⁵ Bq/m³, so the concentration of radionuclide Co-60 in well water is far below the boundary value.
Figure 3. Nuclide concentration in well water.

Figure 4. Concentration of Co-60 in surface water

Figure 5. Concentration of Cs-137 in surface water.
The maximum concentration of Cs-137 in surface water is about 1.84 Bq/m³ in year 101 after closure and the concentration tend to decrease until about 3.31×10⁻²⁹ Bq/m³ in year 2901 after closure of the NSD. If compared to the BAPETEN Chairman Regulation No. 7/2013 on Boundary Value of Environmental Radioactivity, which the maximum concentration of radionuclide in water body is 10⁻² Bq/m³ to 10⁵ Bq/m³, so the concentration of Cs-137 in well water is still far below the boundary value.

**Figure 6.** Individual doses by nuclide (a combination of all pathways).

**Figure 7.** Total annual dose.
From Figure 6 it can be seen that the total contribution of its largest individual dose from Cs-137 radionuclides with a peak value at the beginning of the year amounting to 15.0x10^{-7} \mu Sv/year and the smallest value of 15.0x10^{-13} \mu Sv/year in year 500 after post-closure of NSD.

By looking at Figure 7 seen that the total values of annual dose have a tendency of diminishing from year to year with a peak value of 5.0x10^{-9} \mu Sv/year in the early and the smallest dose is 5.0x10^{-38} \mu Sv/year in year 2600 post-closure of NSD.

The BAPETEN Chairman Regulation No. 4/2013 on the Protection and Radiation Safety in the Utilization of Nuclear Energy defined that dose constraint value for public is 1 mSv/year, so that, the total dose caused from post closure of the NSD is still too far below the dose constraint value.

The result of this safety assessment cannot be compared to the result of the safety assessment that had been conducted in 2012 [6], because the waste data, design of NSD, and the site data are very different. Of course, the result of this safety assessment also cannot be compared to the result of the safety assessment that had been done in India and Korea [9-11], because the waste data, design of NSD and the site data must be different.

If compared to the result of the assessment of radionuclide release scenario to well water and surface water from demonstration plant of NSD that had been performed in 2015 [7], it appears that the difference in result is not so large. The concentrations of radionuclide in well water and surface water in the almost similar ranges of about 10^{-15} Bq/m^3 to 10^{-1} Bq/m^3, especially for Cs-137.

5. Conclusion
The concentration of Co-60 in well water is 4.0x10^{-10} Bq/m^3 in year 200 after closure and the concentration tend to decrease until 3.0x10^{-15} Bq/m^3 in year 300 after closure of the NSD. The concentration of Co-60 in well water is still far below the boundary value that has been defined in regulation.

The maximum concentration of Co-60 in surface water is 1.52x10^{-3} Bq/m^3 in the first year after closure and tend to decrease until 9.44x10^{-26} Bq/m^3 in year 401 after closure of the NSD, so that, the concentration of radionuclide Co-60 in well water is far below the boundary value.

The maximum concentration of Cs-137 in surface water is 1.84 Bq/m^3 in year 101 after closure and the concentration tend to decrease until 3.31x10^{-29} Bq/m^3 in year 2901 after closure of the NSD, so the concentration of Cs-137 in well water is still far below the boundary value.

The total contribution of its largest individual dose is Cs-137 with a peak value at the beginning of the year amounting to 15.0x10^{-7} \mu Sv/year and the smallest value of 15.0x10^{-13} \mu Sv/year in year 500 after post-closure of NSD.

The total value of annual dose tend to decrease from year to year with a peak value of 5.0x10^{-9} \mu Sv/year in the early and the smallest dose is 5.0x10^{-38} \mu Sv/year in year 2600 post-closure, this value indicate that the total dose caused from post closure of the NSD is still too far below the dose constraint value for public (1 mSv/year).

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