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Preliminary conceptual design of borehole disposal facility for disused sealed radioactive sources at Serpong Nuclear Center-Indonesia

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Abstract

Borehole disposal facility is planned to be designed by the Center for Radioactive Waste Technology-National Nuclear Energy Agency of the Republic of Indonesia to dispose the Disused Sealed Radioactive Sources (DSRS). Up to now, the DSRS is still stored safely in the interim storage facilities at Serpong Nuclear Center. Most DSRS come from the industry and hospital sectors. Until 2019, about 3031 pieces of DSRS are being stored at the interim storage facilities in the 200L drum shells and 350L/950L concrete shells. The proposed facility is to accommodate the category 3-5 DSRS. Borehole disposal facilities are planned to be placed at a depth of about 100 m, on the clay formation. Several factors were taken into account in preparing the conceptual design of the borehole disposal facility. Multiple barrier systems are used in the facility. Passive and natural barriers are used to isolate the waste packages from the biosphere. The barriers also provide an effective containment system for long-term safety and function to limit the possibility of human intrusion (security and safety) to the facility. The aim of the paper is to explain the description of the conceptual design of the borehole disposal that will be designed.

Keywords: DSRS, Management, Conceptual design, Borehole disposal

1. Introduction

Generally, a Sealed Radioactive Source (SRS) form is just a small sealed container of radioactive material. The container contains radioactive material with high activity. Usually, it is shaped like a small piece of metal, such as a shirt button size. SRS is widely used in applications that are useful in medical (cancer treatment) and industry (gauging, logging) sectors [1]. Sealed radioactive sources can be found in almost all countries, including Indonesia. They can be found in many places, ranging from small shaped SRS such as a home smoke detector, laboratory smoke detector to a large enough shape like those in a medical hospital/clinic. Technically, IAEA defines radioactive source as “radioactive material that is permanently sealed in a capsule or closely bonded, in a solid form and which is not exempt from regulatory control” [2].

SRS that has been manufactured contain radioactive materials that can produce α, β, γ radiation, and even neutron radiation emissions. According to the requirements of the user, half-lives of isotopes that are used in SRSs commonly vary from short to long half-lives. For the safety of the people and the workers, the radiation emission requires SRS to have a metal shielding. Minimal shielding is needed for the SRS with the lowest radioactivity (such as the SRS in a home smoke detector), whereas the SRS with the highest activity (categories 1-2) may need a thick and heavy shielding at about more than 1,000 kg of metal shielding.

Recently, based on the licensing records in BAPETEN (nuclear regulatory body in Indonesia) in the year of 2017, the number of SRS which is circulating in Indonesia has reached more or less 6424 sources, which are spread in many sectors, especially in hospitals and industries [3]. After being applied in the hospital or industry, the radiation emission energy of SRS will be reduced. The SRS will eventually become ineffective and then declared as the Disused Sealed Radioactive Sources (DSRS). The application licensing of the SRS that has become DSRS has also been completed, and therefore the DSRS shall be managed further.

In terms of DSRS management, Cochran et.al. provides several options that can be used such as radioactive decay, reuse and recycling, return to the vendor/repatriation, storage and dispose of the sources [4]. Currently, most DSRS is stored in the user's facilities before being sent to the government facilities. Because they can pose the radiation hazard, it is not possible to store all DSRS until the decay of their radioactive sources becomes no longer dangerous. For example, to store ^{137}Cs radioactive sources, it requires about 1000 years of storage to decay the categories 1-2 DSRS to safe levels. It is very difficult to imagine how to exercise active control over the long period of time to radioactive sources at a waste storage facility. The reuse and recycle processes are only efficient for the DSRS with a high activity level or the ones that are still in accordance with what the users need. As for the DSRS repatriation process, it is only economical for the DSRS which is included in categories 1-2. This option is expensive and difficult due to some countries that do not have adequate infrastructure (equipment and human resources) for this option yet [5].

For cases in Indonesia, the DSRS that is not repatriated to the vendor's countries will be transferred to the National Nuclear Energy Agency/BATAN (cq. Center for Radioactive Waste Technology/PTLR) for storage. The DSRS is being stored safely at (PTLR), in the Interim Storage for High Radiation Waste / PSLAT bunker, interim storage / IS-1 and IS-2 facilities [6]. Most of the DSRS is still in their container and arranged on racks at the IS-1 and 2 facilities because the dismantling process is not finished yet. Nowadays, the dismantling and encapsulating process of DSRS Category 3-5 have already been carried out by the PTLR technicians and have always been under the supervision of experts from IAEA. Long term storage method does not provide comfort and safety feeling for radiation workers due to the presence of radiation hazard at their work location. For this reason, it is necessary to develop a conceptual design of an inexpensive disposal system for DSRS that meets the safety standards for the workers, the public, and the environment. One of the options is the borehole disposal system. This system is also able to prevent the possibility of intrusion by irresponsible parties or people. For this reason, IAEA proposed the BOSS (Borehole Disposal of Spent Sources) concept which was introduced by South Africa [7-9]. The borehole disposal is a multi-barrier disposal system for DSRS. This facility is equipped with the layered engineered barriers system (confinement, isolation, and multiple safety functions) to prevent the spread of radionuclides to the environment and the occurrence of human intrusion in the facility. The role of the host rock in the borehole disposal system is to delay and disperse the release of radionuclides from the waste matrix through the disposal system. The aim of the paper is to describe the conceptual design of the borehole disposal which will be designed, and to explain the conceptual design requirements for the borehole disposal facility.

2. Materials and methods

The facility was planned to be used for the DSRS categories 3-5 disposal. Protection of human health and the environment was carried out to ensure that the present and future conditions of possible radiation hazards were the fundamental requirements in the disposal facility design concept, including the design of the borehole disposal facilities. For the long-term safety, the facility also required passive system barriers consisting of conditioned and waste packages, repository lining, backfilling materials, and other engineering barriers in the disposal section.

The preparation of the conceptual design of the borehole disposal facility was carried out by paying attention to the goals of the facility towards the fulfillment of environmental safety requirements so as not to endanger human life in the future. The collection of relevant information was done through literature study by exploring some disclosed documents such as journals, proceedings, technical documents, activity reports and others. This information included the source of the waste inventory, the site location and its description, containment design, borehole disposal design, disposal process, and site-specific safety assessments. All the information was closely related to the conceptual design of the borehole disposal facility aspects.

3. Results and discussion

To ensure the protection of human health and the environment, some factors are taken into consideration in the borehole disposal conceptual design. For example, the institution's infrastructure should be able to control the facility, feasible to implement technically, easy to manage, and use relatively conventional storage methods. The design should also minimize the need for active maintenance, economically feasible to implement (depends on the financial situation), adjustable to the size and number of sources that need to be stored, and can contribute to the general aim of the safety objective of radioactive waste management (protection of human health and the environment, at present and in the future) [7].

The conceptual design of the borehole disposal facility does not only consider technical factors such as infrastructure, storage methods, and the safety of the borehole disposal facility but also the non-technical factors such as financial state [7]. Those considerations are needed so that the planning of the conceptual design can be carried out independently by BATAN experts together with other domestic stakeholders, without ignoring the main principles of radioactive waste management. The next section will discuss the requirements to fulfill the conceptual design of the borehole disposal and their assumptions.

3.1 Waste inventory

The DSRS are now being stored safely at the PTLR, in the Interim Storage for High Radiation Waste / PSLAT bunker, interim storage / IS-1 and IS-2 facilities with a strict security system, CCTV control, and electronic access system. There are category 1-2 DSRS stored neatly on the rack at IS facility as shown in Figure 1. There are about 34 sources. All radioactive sources are still stored in their cylinder head. This DSRS type comes from the hospital and was used for teletherapy treatment.

Figure 1 DSRS categories 1-2 storage.

The category 3-5 DSRS have many types of radiation emissions such as α, β. γ and even n radiation emissions. They will be stored in several types of containments and storage facilities. The DSRS with neutron transmitters originating from ^{252}Cf, Am-Be, or Po-Be radionuclides will be stored in the PSLAT bunker facility. However, the DSRS containing radionuclides such as ^{60}Co, ^{137}Cs, ^{241}Am, ^{85}Kr will be stored at the IS facilities in the 350L concrete shell containers. The categories 3-5 DSRS are stored in the 350L concrete shell at the IS and PSLAT bunker facilities [6] as shown in (Figure 2)

Figure 2 The DSRS at the bunker facility and 350L concrete shell.

The sources from the dismantling results are put in a capsule container made of stainless steel, and then the capsules are collected in a 200L drum shell. The 200L drum shell is coated with a liner or concrete layer in the inside of the drum that functions as the shield for the radiation emission coming from the SS capsule. The shape of the SS capsule and the 200L drum shell can be seen in (Figure 3) [6].

Inventory of the source is the main feature of the borehole disposal conceptual design, especially during the preparation of the conceptual stage. The inventory also includes detailed information on the actual number, activity, physical dimensions, identification numbers, and physical condition of the sources. From the number of radioactive sources that will be ready to be disposed of, the required volume of the borehole disposal facility can be determined. The number of DSRS in the PTLR inventory collected until 2019 is shown in (Table 1) [6].

Figure 3 The shape of SS capsule and 200L drum shell.

Table 1 The inventory of DSRS at PTLR-BATAN, FY 2019

No.	Type	Containment	Number (pieces)
1.	Non-Radium (^{60}Co, ^{90}Se, ^{85}Kr, etc.)	350/950L concrete shells	1,151
		200L drum shells	
2.	Non-Radium (big dimension)	racks, unconditioned DSRS	166
3.	^{192}Ir and ^{75}Se	Container for Iridium	1,004
		200L drum shells	
4.	^{226}Ra (lightning rod, needle)	200L drum shells	596
5.	Smoke detector	200L drums	114
		Total	3,031

3.2 Site location and its description

The site of the facility is located at the National Nuclear Energy Agency site at Serpong Nuclear Center (SNC) in South Tangerang. The position in around -6.348902°; 106.661693° at an elevation of 88 m, see Figure 4. The geomorphological conditions of the location indicated as an alluvium plain with the constituent rocks are alluvium which consists of clay, silt, sand, gravel, crust, and lumps, and the topsoil is in the form of clay-sand. The SNC regional lithology is mainly influenced by volcanic activity in southern of the location, as well as by exogenous processes to volcanic rocks with highly intensive [10].

Figure 4 Location of selected site for borehole disposal facility from Google Earth.

The characteristics of the soil stratigraphy around the candidate of the borehole disposal location were known from drilling and sampling the soil's core results. The sampling activity has been carried out at the DH-2 point with a depth of up to 100 m. The obtained results can be seen in (Figure 5). The soil residuals on the topsoil parts (0-8.8m depth, as A and B soil horizons) stack on the Serpong formations (8.8-24.8 m depth) and Bojongmanik formations (24.8-100 m depth), which are the three main stratigraphic units at the drilling location in DH-2 points. In general, siltstone that is intercalated with sandstone, limestone, or limy-siltstone and limestone that is intercalated with siltstone and claystone at the depth around 70-80 m were found in the soil stratigraphy [11].

The shallow groundwater distribution in the area is controlled by the distribution of lithology and its morphological conditions, with the depth ranging from 5.06 - 11.35 m [12,13]. The test results and the permeability calculations in Bojongmanik formation rocks show that the value varies greatly in the range of 10^{-3}-10^{-10} cm/s, due to inhomogeneous rocks conditions [14].

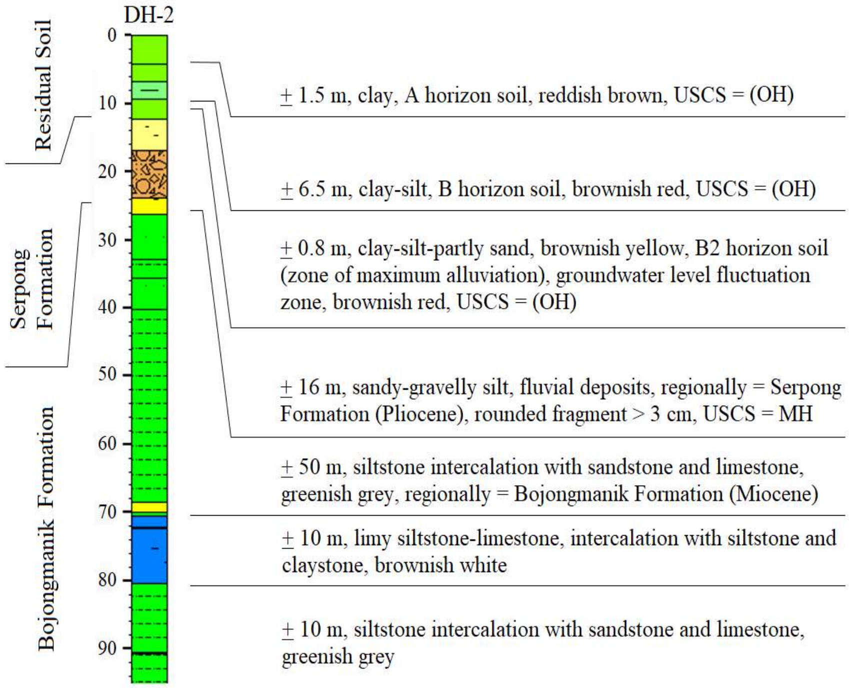

Figure 5 Soils stratigraphy at DH-2 point.

The hydraulic conductivity values of the rocks in the zone are very affected by the presence of burly on the rock which is quite intensive. Based on the lithology observation, the siltstone has soft white feldspar beads with fine size. It is expected that the feldspar granules change the physical properties of the siltstone into a rather sandy shape, resulting in bigger rock pores and bigger value of hydraulic conductivity than the theoretical value of siltstone [14].

3.3 Containment design

The overall safety performance of the borehole disposal system is not very dependent on a single barrier or function. To increase the safety assurance, multiple barriers and various safety functions should employ a number of complementary engineered and natural barriers. This action is done to provide assurance in the long-term safety. One way is to provide a container made of a corrosion-resistant material for the DSRS that is able to provide a lifetime container for about a thousand years, such as the 316L grade stainless steel. The radioactive source is contained in a 316L stainless steel capsule that contains one or more DSRS and is tightly closed. The capsule is then put into a container for disposal which is made from SS 316L as well. The gap between the container and the capsule walls containing DSRS is then filled with cement concrete. The cement concrete layer will function as physical and radiation protection. It will also serve to condition the groundwater chemically.

Figure 6 shows the disposal container or waste package for DSRS schematically [9,15].

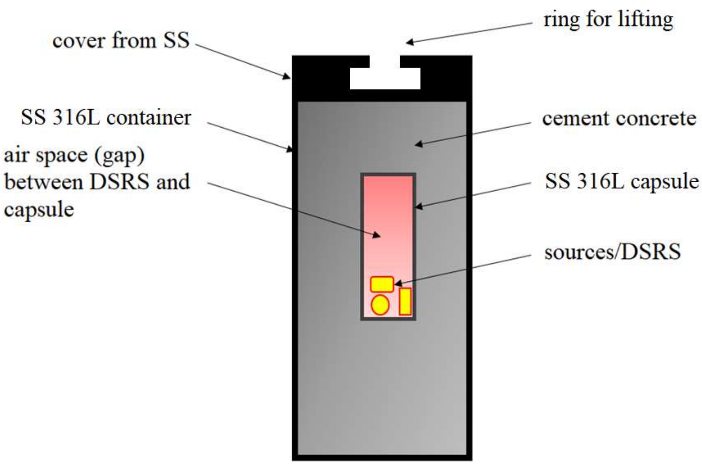

Figure 6 Schematically the disposal container for DSRS [9].

3.4 Borehole disposal design

The borehole disposal facility is planned to be designed by the Center for Radioactive Waste Technology-National Nuclear Energy Agency of the Republic of Indonesia at Serpong Nuclear Center. The facility will be used for the disposal of categories 3-5 Disused Sealed Radioactive Sources (DSRS). Figure 7 shows a model of a borehole disposal facility. It can be seen that the borehole facility is placed at a depth of land and composed of several stratigraphic units.

Since the waste package is received by the operator, the operator of the borehole disposal facility is responsible for the security of the DSRS waste package. It is necessary to make security arrangements for the DSRS waste package. The level of security arrangements should reflect the potential damage to the facility and the assessed risk of irresponsible people in removing the waste. It should at least includes measures to prevent unauthorized access to the site during site operations and in the post-closure period to prevent human intrusion and/or an illegal removal of the waste by someone, whether they are intentional or not.

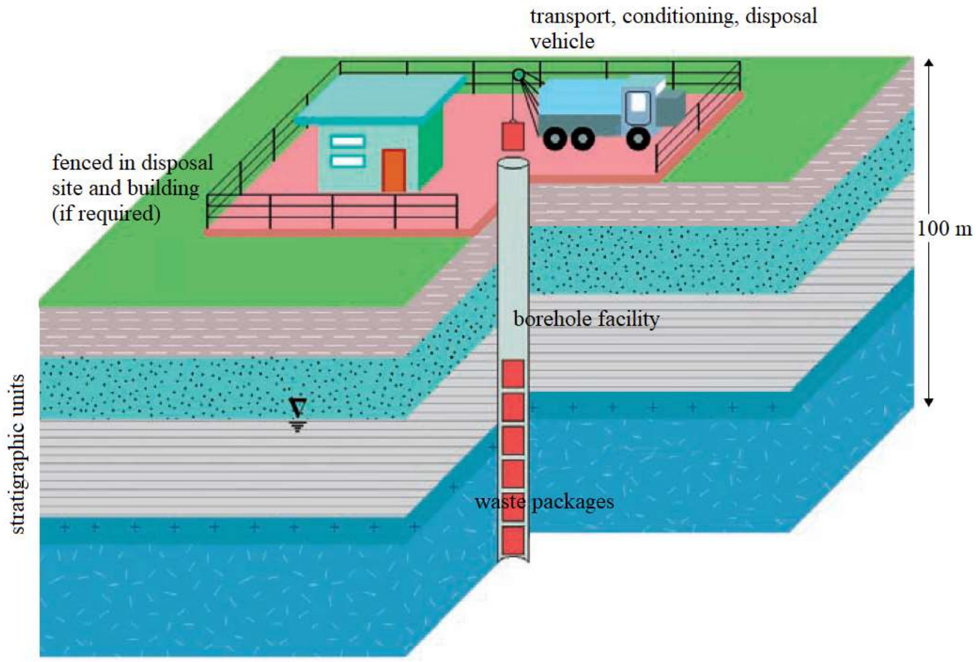

Figure 7 A model of a borehole disposal facility [9].

Security facilities such as guards, fences, monitoring and surveillance system surrounding the facility are the physical barrier systems in the repository/borehole disposal facilities. The site office is sometimes also needed to serve the administrative activities during the borehole disposal operation period. Overhead cranes as temporary facilities are used to carry out the activities to lift the DSRS waste packages into the hole. The crane equipment is needed during the borehole disposal facility operations.

The planned repository concept is a borehole drilled in a clay formation. The placement zone of the waste package is under the groundwater table. Borehole disposal facilities are planned to be placed at a depth of about 100 m or more, depending on the geological formation that will be occupied. The multibarrier disposal system will be used in the designed borehole disposal concept, consisting of passive and natural barriers to isolate the waste packages from the biosphere. The layout of the borehole disposal concept is shown in (Figure 8).

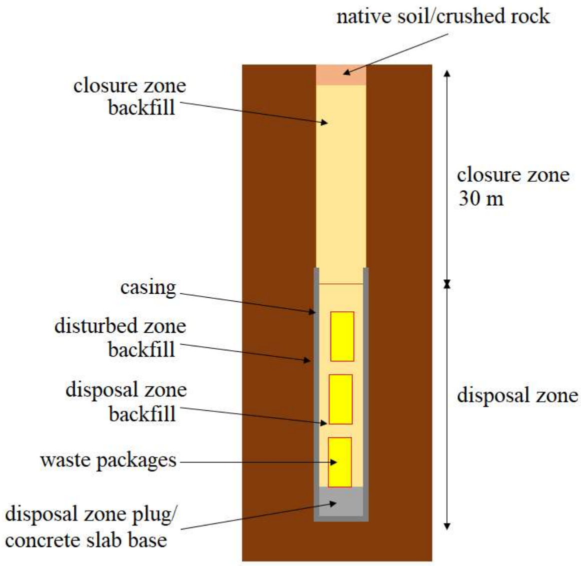

Figure 8 Schematic of the borehole disposal [4].

The multibarrier concept is applied for the long-term safety of the facility. The geological media must have the impermeable property and able to prevent the possibility of radionuclides release. The gap between the pipe casing and the geological formation is filled with cement paste as a disturbed zone backfill or casement wall. Cement paste which is hardened around the casing can serve as a barrier against the radionuclides migration from the repository, and can also be a barrier to the water flow between the different layers through which the borehole passes. The hole is encased with PVC or steel pipes that also function as a smooth casement wall. The disposal containers or waste packages and capsules made from stainless steel will serve as a containment to the DSRS. The barriers as the whole system will postpone the contact of waste packages with the groundwater and retard the migration of the radionuclides back to the biosphere, allowing much of radionuclides to decay before they disperse into the environment [16]. At the boundary between the closure zone and the disposal zone, a deflection plate (anti-intrusion steel plate, 10 mm thickness) is provided to prevent the disruption of the waste package in the disposal zone from any undesirable events such as a direct drilling from the above of the borehole [9,17].

The bottom end of the disposal zone is plugged with a concrete slab. The native soil from the site or crushed rock is stuffed into the mouth of the hole of borehole with 3 m thickness. At the end of the disposal phase, all borehole facilities may be sealed and closed individually or collectively. The facility is then declared closed when all boreholes are backfilled and sealed.

The engineered barrier materials such as casing, backfill materials, containers, stainless steel capsule of DSRS might be acting as a barrier to prevent the possibility of radionuclides transport. The barriers will provide an effective containment system for long-term safety and limit the possibility of human intrusion (security and safety) to the facility. In order to prevent some possible intrusions from outside, passive institutional controls are implemented which include: (a) long term markers; (b) restrictions on land use and ownership; (c) preservation of records; and (d) financial assurances [18]. In general, the locations with the following characteristics should be avoided: underground natural resources, rapid surficial erosion, low pH, aerobic locations, high-chloride groundwater due to accelerating corrosion of the stainless steel barriers.

Estimated costs incurred for the construction of the borehole disposal facility are around 100,000 to 200,000 USD depending on the site condition, excluding the costs of manufactured waste packages, surface facilities, transportation, and licensing [9,16].

3.5 Disposal processes

The waste package is loaded into the facility by using an overhead crane. In the disposal zone, the packages are stacked at a certain distance with another one. Backfill materials made of cement paste is put in between the waste packages to give a certain distance to the waste package. After the capacity of the disposal zone is reached, the closure zone above the wastes packages is sealed off with concrete as closure zone backfill. Casings in the closure zone can be removed and the closure zone is continuously filled with backfill materials. The mouth of the borehole is then covered using a native soil in the form of crushed soils and rocks.

In designing, the depth of the borehole disposal facility between the disposal zone and the surface should be at least 30 m. The purpose of making the distance is to avoid the possibility of human intrusion by excavation and construction of the tunnels. At the SNC site, the initial boundary of the closure zone is determined by considering the existence of the valley in the south-west direction of the borehole disposal location candidate with a depth of 18 m (E). This constraint improves the minimum depth of the discharge zone into E + 30 m if the disposal zone plug is about 1 m. The length of the disposal zone is the result of the sum between the number of packages and the distance between the containers in the borehole. The formula is n (h+d) m, where n is the number of waste package, h is the height of waste package and d is the distance between containers. Thus, the length of the disposal zone is as follows:

$$100m = \big((E + 30) + n(h + d) + 1\big)m \quad (1)$$

$$\mathrm{n(h + d)} = 100m - \big((18 + 30) + 1\big)m = 51m \quad (2)$$

Assuming that the waste package is 25 cm long and placed in the borehole at the distance of 0.75-1 m from each other [9,19], the maximum number of waste packages which can be placed in the 51 m long disposal zone are 40 to 50 packages. Closer distance among the packages will produce a more concentrated contaminant plume in the groundwater layer, and this condition will affect the safety of the environment in the post-closure period of the borehole disposal facility. The number of disposed packages per-borehole will be determined in advance from the site-specific safety assessment, as well as the amount of radioactivity allowed, depth, and length of the disposal zone [9].

3.6 Safety assessment

Post-closure radiological safety assessment is needed to demonstrate the safety conditions of the borehole disposal facility during the post-closure period. The concept of an ideal borehole disposal facility is a suitable combination of inventory, near field design, and geological environment, which is able to provide a safe solution for the disposal of long-lived and short-lived radionuclides [4,20].

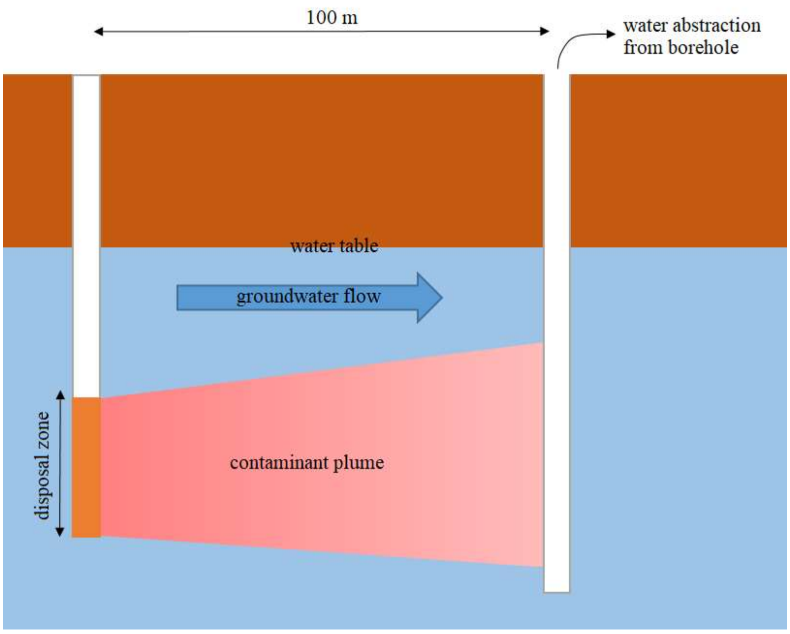

Figure 9 Conceptual model of safety assessment of radionuclides leakage for the disposal facility located in the saturated zone.

To predict the condition of the environmental safety of the borehole disposal facility location, a safety assessment with a site-specific condition needs to be performed to determine the amount of radioactivity of radionuclide that can be disposed safely at a certain location. The objective of safety assessment is to determine the acceptable level of radiation protection for humans and the environment which can be achieved at present and in the future. Safety assessment is carried out by using the Improvement of Safety Assessment Methodology (ISAM) method which has been recommended by the International Atomic Energy Agency (IAEA) [21]. The scenario used to carry out the safety assessment following the conceptual model for saturation conditions is shown in (Figure 9) [9]. The radionuclides release scenario is implemented with the assumption that there are leakage and radionuclides leaching from the disposal zone which form a contaminant plume at the borehole facility. In the saturated zone, the groundwater moves parallel to the surface of the ground which results in the radionuclide leaching out. Contaminated groundwater is pumped up through extraction boreholes at a distance of 100 m by the people to be used as drinking water, irrigation, inland fisheries, etc. This produces radiation doses to the people who live around the site and use the contaminated groundwater. Some radionuclides will be absorbed strongly into engineered and natural barriers such as concrete backfill/wall of borehole and rock, making their migration rate retarded. This situation will cause a very slow leaching process of radionuclides from the facility to the groundwater. Consequently, the safety assessment will indicate that the environment seems to be able to accommodate the radionuclides release if the borehole facility leaks. Several key factors to derive the safety assessment appropriately under saturation conditions must be considered. In ISAM methodology, some parameters such as hydraulic conductivity, hydraulic gradients, filled water porosity, and sorption coefficient (Kd) of relevant radionuclides that are absorbed to the engineered barriers and surrounding rock were considered [22]. By estimating and comparing all the safety assessment scenarios with various parameters, an appropriate safety assessment calculation case can be chosen. The safety assessment can also show how the containment system provided by the waste package is capable to decay radionuclides to negligible levels. AMBER and RESRAD software provide calculation models for quantitative estimation of the occurrence of radionuclide releases from waste containers through various geological media via various pathways to the biosphere [23,24].

By considering the material balance of each connected compartment, a quantitative estimation of the radionuclide release into the biosphere can be made. Evaluation of the dose received by humans and the environment is the final stage of a safety assessment process. Radionuclides released from a facility penetrate various geological media into the biosphere as well as via various pathway routes. By using a conversion factor, the radionuclide flux will be converted into a dose that is accepted by humans. Safety assessment also takes into account the mathematics of the radionuclide decay chain in each compartment model of the biosphere system.

The material balance in the compartment for mass of radionuclide N_i is calculated as follows [25]

$$\frac{dN_i}{dt} = \sum_{j \neq i} \lambda_{ji} N_j + \lambda^M M_i + S_i(t) - \sum_{j \neq i} \lambda_{ij} N_i - \lambda^N N_i \quad (3)$$

where, λ is decay constant, M is mass of parent nuclide, and S is source term in each compartment i. The flow rate of nuclide from one compartment to the adjacent compartment is proportional to the mass transfer coefficient λ_{ij}. The equation (3) can be applied to calculate the feasibility of a waste storage design. The containers placed in the disposal zone will degrade. Radionuclides are released from the small holes of the containers, and then the radionuclides are ready to be transported through the surrounding geological media and groundwater. Finally, radionuclides reach the biosphere where they give the rise doses to the human and the environment. The results of the safety assessment become one of the considerations for the regulatory body to determine the feasibility and safety of a disposal facility design before its license is approved.

Until the year of 2018, no country has prepared the safety case for the operational and post-closure safety of the specific borehole disposal facility for DSRS. Therefore, until that year there were no examples of safety cases available for the borehole disposal systems. However, recently, the safety cases which have been provided by Ghana and Malaysia are expected to be used as a starting point for preparing the safety case for the specific borehole facility [4]. To prepare the safety assessment program of the borehole disposal facility, BATAN already has AMBER and RESRAD software to assess the engineered and natural barriers performance and to estimate the post-closure dose of radioactive waste disposal facilities including the borehole disposal facilities.

4. Conclusion

Preparation of the conceptual design of the borehole disposal facility has been developed to manage the DSRS collected at the interim storage facility. The borehole disposal facility is equipped with a multi-barrier system to provide safe conditions for a long period isolation condition, where every barrier support each other to prevent the possibility of released radionuclides from the disposal facilities into the environment. Post-closure radiological safety assessments are conducted to demonstrate the safety conditions of the borehole disposal facility during the post-closure period. The technology developed for the borehole disposal concept can be used and implemented safely. It is relatively conventional and easily managed so that BATAN's infrastructure can fully control the facility.

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