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Demonstration of the Stability of the Engineered Barrier System of the Borehole Disposal System for the Disposal of Disused Sources in Ghana

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Abstract

Ghana has opted for the Borehole Disposal System (BDS) as the long-term management solution for disused sources generated in the country. The design of the BDS integrates the engineered barrier system (EBS) with the natural barriers into its overall safety concept. The stability of the EBS to augment the natural barriers to ensure the long-term safety of the BDS has been demonstrated with the aid of a scoping tool. The tool was used to calculate the failure times of the EBS based on the hydro-chemical data determined at the proposed site for the saturated zone under aerobic and anaerobic conditions. Failure times were influenced by variation in thickness of the engineered barriers and the order in which the engineered barriers would be conceptually designed to contain the radionuclides. The time calculated for the radionuclides to decay to the exemption levels showed that, the engineered barriers appeared stable to contain all the disused sources in the case of disposal in the saturated anaerobic zone for one of the scenarios considered.

Keywords: Stability, Engineered Barrier System, Borehole Disposal System, Disused Sources

Introduction

The application of radioactive sources has increased and there is general awareness in the country of the numerous economic benefits to be derived from their application. They are being used in these areas of the Ghanaian economy: medicine, industry, agriculture, research and teaching purposes. Many of the radioactive sources are in the form of sealed radioactive sources (SRSs). A sealed radioactive source (SRS) is a radioactive material that is permanently sealed in a capsule or bonded and in a solid form [1]. SRSs are typically small in sizes. Despite their predominantly small physical size, many of the SRSs, e.g., the industrial and medical sources, contain high concentrations of radionuclides typically in the giga becquerel (GBq) to peta becquerel (PBq) range [2].

Ultimately, radioactive waste is expected to be generated from the application of radiation sources in the country and therefore needs to be managed based on national and internationals principles and laws as well as adopting best practices in this regard. Currently, the radioactive waste generated in the country is mainly disused sealed radioactive sources (DSRSs). When the activity of the radioactive source decays to levels such that it cannot be used for its authorized purpose, it is referred to as a DSRS [3, 1]. A DSRS may still be highly radioactive and potentially hazardous to human health and the environment. Hence, if not managed safely and securely, it can still pose serious health threat to humans and risk to the environment, and this is evident from the number of accidents that have occurred worldwide [4]. DSRSs also present security concerns as the sources can be stolen and their radioactive materials used in Radiological Dispersion Devices (RDD) also known as dirty bombs for acts of terrorism [5, 6,7].

From the above reasons, it is clear disused sources need to be given all the necessary attention to ensure their safety and security management from predisposal to disposal. The basis of the safe and secure management of DSRSs are provided for in the International Atomic Energy Agency (IAEA) Safety Fundamentals Principles [8], which sets out the fundamental safety objective and principles that needs to be applied to all facilities and activities in radioactive waste management, including the disposal of radioactive waste.

The radioactive waste management practice in Ghana entails safe and secure storage. The DSRSs are thus collected from the user's facility, characterized and stored. Storage is an important interim step, but long-term storage is not considered sustainable for hundreds to thousands of years and in many cases may represent a high-risk situation with regard to both the health hazard and the security threat posed by high activity long lived sealed sources. For these reasons, Ghana through the Ghana Atomic Energy Commission (GAEC) intends using the IAEA Borehole Disposal System (BDS) for disposal of the DSRSs in storage.

The BDS is the first of its kind in the world and currently, Ghana and Malaysia are the two countries that are exploiting the implementation of this disposal system. Since this disposal system is intended to last for several hundreds to thousands of years, special attention is focused on the performance of the EBS on the host environmental conditions to provide the required level of safety. The selected EBS should be sufficiently stable to contain the radionuclides for the activities to decay to the excerption levels. It is for these reasons that, in this study, the stability of the EBS has been demonstrated to evaluate their impact on the long-term safety of the BDS.

Conceptualised Design of the Borehole Disposal System

The BDS (shown schematically in Figure 1) is a multi-barrier disposal system that entails the emplacement of conditioned DSRSs in an engineered facility drilled and operated directly from the ground surface [9]. The BDS uses stainless steel capsules and containers, and cement barriers to contain and isolate the DSRSs from the biosphere. The disposal borehole is 260 mm in diameter and is drilled to a depth which depends on the site characteristics but greater than 30 m deep. The borehole is lined with high density polyethylene (HDPE) tubing with cement grout pumped into the gap between the lining and the host rock as well as the base of the lining to provide a bottom seal (Figure 1). Three distinct zones can be defined in the disposal borehole:

The Disposal Zone

This is the zone inside the casing where the waste packages are disposed. As indicated in Figure 1, this study considered a total depth of 100 meters for the BDS. The base of the disposal zone is 95.5 m from the ground surface. The base of the borehole is emplaced with a 0.5 m thick 'plug' of backfill cement grout. After all the waste packages have been positioned, backfill cement is poured over them to cover the 12.5 mm thick space between the containers and the wall of the casing, as well as a volume on top of the waste package. The backfill layer on top of each waste package should be at least 750 mm deep. Together with the waste package, this constitutes a pitch height of about 1 m per waste package. Since the study assumed 10 waste packages to be disposed, the total depth of the disposal zone is about 10 m.

The Closure Zone

This is the zone between the disposal zone and the ground surface. The closure zone is about 90 meters deep as shown in Figure 1, which is a significant depth for minimising the risk of human intrusion and limiting any intrusion that might occur [9]. After emplacement of the last waste package, the upper portion of the HDPE casing will be withdrawn out of the borehole. The casing will be withdrawn out of the borehole at 1 m above the last disposal package. This eliminates the possibility of a quick transit route to and from the disposal zone after the casing has degraded.

An anti-intrusion (deflecting) steel plate will be fitted above the casing in order to re-direct into the surrounding rock any drill bit hitting the plate. The thickness of the anti-intrusion plate is about 15 mm and is normally rectangular in dimensions related to the inside diameter and should generally rest at an angle of about 45° inside the borehole. The anti-intrusion plate should then be surrounded by backfill grout. Once the deflecting plate is fitted, the closure zone is then backfilled with the same cement grout used in the disposal zone to a depth of 5 m below the surface of the ground. The natural soil and/or crushed rock is then used to cover the final 5 meters of the closure zone [10].

The Disturbed Zone

This is the zone between the casing and the wall of the borehole. During the drilling operation, voids and cracks in the host geology immediately adjacent to the borehole are assumed to be filled with the same cement grout used for backfilling the disposal and closure zones. In addition, a gap of around 50 mm between the borehole wall and the casing is backfilled with cement grout using a pressure grouting technique [11]. As indicated in Figure 1, centralisers are used to secure the casing and ensure that it is centred in the borehole. The centralisers, which are constructed of thin mild steel plates, are mounted vertically to avoid impeding the flow of the backfill slurry [10].

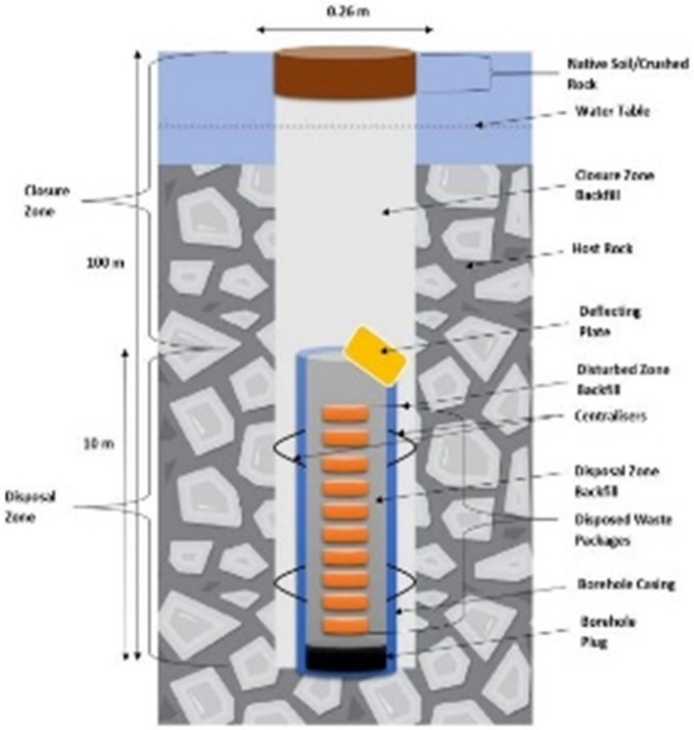


Figure 1: Schematic representation of the BDS, showing the position of the disposed waste packages (diagram not drawn to scale)

Materials and Method

Location and Description of the proposed BDS Site

A site within the GAEC Research Reactor premises located at Kwabenya, in the Ga East Municipality of the Greater Accra region has been selected as the repository site for implementation of the BDS. The proposed location is on an area that was originally developed for a "Radon" facility in the early 1960s for the possible storage of DSRSs and spent fuel. The area lies within latitude 5^{0}6’7” N to 5^{0} 6’9” N and longitude 0^{0}2’W to 0^{0}26’W, at an elevation of 64 m.

The whole of the site is covered by loose unconsolidated and weathered material that is generally a few metres deep but which sometimes extends to a considerable depth, especially in the western part of the site [12, 13]. The major geological formations in the area comprise the Togo series and the Dahomeyan system, both of which are of Precambrian age [14, 15]. The Togo series consists of phyllite, schist and quartzite. The Dahomeyan system comprises schist, gneisses, and migmatites. The Togo series occupies the north-western section of GAEC and occupies the highland areas whereas the Dahomeyan-outcrop in the low-lying areas [14, 15, 16].

Materials

Proposed Materials for the Engineered Barrier System

The EBS plays a pivotal role in ensuring containment of the radionuclides for hundreds to thousands of years thus allowing the radionuclides to decay to exemption levels. The materials to be used should be resistant to degradation under the conditions prevailing in the environment (e.g., conditions of chemistry and temperature) and selected also to limit any undesirable impacts on the safety functions of any element of the disposal system. This requires that during that period the capsule and disposal container corrosion is sufficiently slow and uniform and that the capsule and disposal container are sufficiently strong to ensure their integrity.

Slow corrosion could be achieved by selecting a corrosion resistant material for manufacturing of the capsule and disposal container, such as stainless steel, carbon steel, titanium alloy, copper, ceramic materials, plastic composites and cast iron. Stainless steel is the preferred material based on its corrosion resistance and heat-resistant properties. Stainless steel of Type 316L has been identified to be used in manufacturing the capsules and the disposal containers. Sulphate-resistant cement grout is also assumed to be used for the backfill and containment barrier.

Components and Geometry of the Engineered Barrier System

The components of the EBS evaluated are the capsule, disposal container, a physical barrier and chemical barrier (cement) known as containment barrier and the borehole backfill material (cement). The stability of the EBS of the BDS is the timescale over which the engineered barriers are assumed to function and operate as designed. The overall safety of the BDS could be determined by the performance of the EBS with the natural barriers, and this could be influenced by the thickness of the considered EBS to contain the DSRSs and isolate them from the biosphere. The thickness therefore, plays an important role in order to demonstrate the stability of the EBS to ensure the long-term safety of the disposal system.

The chosen thickness for the reference design using the dimensions of the capsule, disposal container and containment barrier is presented in Table 1. In order to assess the influence of the thickness, and help in a comparative analysis of the selected thickness of the proposed materials for the engineered barriers, the reference design thickness was varied. As a result, the reference design thickness for the capsule and container was reduced by half and then doubled; and the corresponding thickness for the capsule, disposal container and containment barrier were calculated as shown in Tables 2 and 3.

Table 1: Dimensions of the capsule, disposal container and containment barrier for the reference design thickness

Waste Package Component	Length (mm)	Inside Diameter (mm)	Outside Diameter (mm)	Thickness (mm)
Capsule	150	55	61	3
Containment Barrier	187	61	103	21
Disposal Container	199	103	115	6

Table 2: Dimensions of the capsule, disposal container and containment barrier with the reference design thickness reduced by half

Waste Package Component	Length (mm)	Inside Diameter (mm)	Outside Diameter (mm)	Thickness (mm)
Capsule	147	55	58	1.5
Containment Barrier	187	58	103	22.5
Disposal Container	193	103	109	3

Table 3: Dimensions of the capsule, disposal container and containment barrier with the reference design thickness doubled

Waste Package Component	Length (mm)	Inside Diameter (mm)	Outside Diameter (mm)	Thickness (mm)
Capsule	156	55	67	6
Containment Barrier	187	67	103	18
Disposal Container	211	103	127	12

Disposal Zone of Interest

Disposal of DSRSs using the BDS may occur either in the unsaturated or the saturated zone. The proposed site has a shallow water table which fluctuates between 9 to 15 m from the ground surface depending on the season. For the BDS, the minimum depth the waste packages are emplaced should be at least 30 m from the ground surface. Also, to minimise the likelihood of inadvertent and deliberate human intrusion, the waste packages are to be emplaced far from the ground surface. Based on this, the study assumed disposal to occur in the saturated zone under aerobic and anaerobic conditions. The hydro-chemical parameters used for this study are given in Tables 4 and 5.

Table 4: Site Hydrogeological Parameters for Disposal in the Saturated Zone

Parameter	Value	Source
Hydraulic Conductivity	4.49m/y	Highest value obtained from the drilling report
Hydraulic Gradient	0.034m/m	Obtained from the drilling report calculations
Water-Filled Porosity	0.1	(1)

(1) This parameter could not be determined from the site; hence a generic value was used [11]

Table 5: Site Geochemical Parameters for Disposal in the Saturated Aerobic and Anaerobic Zone

Parameter	Aerobic Value	Anaerobic Value	Source
pH	6.68	6.68	From site characterization report
Eh	24.3mV	-281mV	(2)
Chloride Concentration	1800mg/l	1800mg/l	From site characterization report
Sulphate Concentration	238mg/l	238mg/l	From site characterization report
Total Inorganic Carbon	415.58mg/l	42.52mg/l	(2)

(2) These parameters could not be determined from the site; hence generic values were used [11].

Activity and Allocation of DSRSs into Waste Disposal Containers

Based on the inventory to be disposed and the dimension of the sources, ten (10) waste packages were assumed to be used in conditioning all the DSRSs for disposal. The activity and allocation of the DSRSs into the disposal containers are shown in Table 6.

Table 6: Activity and Allocation of DSRSs into Disposal Containers

Radio-nuclide	Physical/Chemical Form	No. of Sources	Total Activity (Bq)	No. of Capsule(s)	No. of DisposalContainer(s)
Co-60	Metallic/solid	96	3.37E+10 (1)	4	4
Sr-90	Ceramic/glass	30	6.92E+09	1	1
Cs-137	Salt	40	1.14E+10	1	1
Pu-239	Metallic	12	2.70E+07	1	1
Am-241	Powder/pellet	110	8.96E+09 (2)	2	2
Ra-226	Metallic	6	9.93E+09	1	1
Total		**294**	**7.09E+10 (3)**	**10**	**10**

1. Total activity of Co-60 (both category 2 and 3-5 sources)

2. Total activity of Am (both Am-241 and AmBeCs)

3. Total activity of all radionuclides to be disposed

Methodology

The Scoping Tool

The scoping tool was used to calculate the failure times of the engineered barriers evaluated. The tool implements the cement degradation model and the corrosion model of the capsules and containers. The tool gives an indication of the failure times of the engineered barriers and the potential suitability of the site based on the site's hydro-chemical characteristics.

Cement Degradation Model

Cement degradation is a complex process but is represented by a simple model in the scoping tool [10,17]. The cement degradation progresses according to the number of times the water in the cement pores is flushed by the groundwater. The cement grout degradation proceeds through four stages based on the research described in [18] as follows:

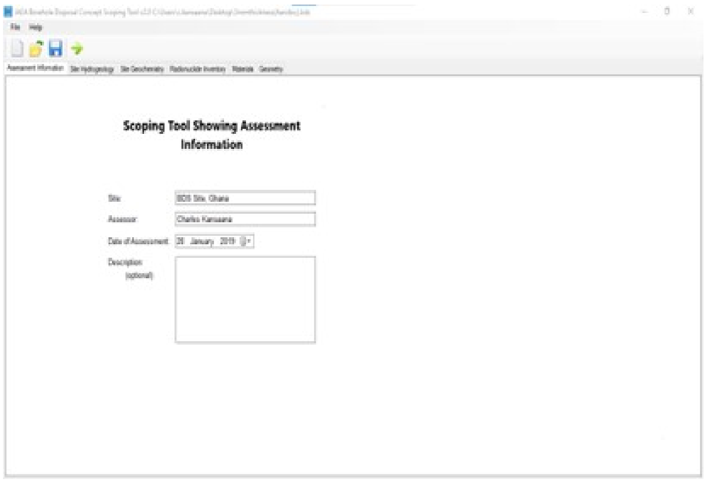
- Stage 1: Porewater pH controlled by NaOH/KOH, pH 13.5;
- Stage 2: Porewater pH controlled by $Ca(OH)_2$, pH 12.5;
- Stage 3: Porewater pH evolves from control by $Ca(OH)_2$ to background groundwater pH;
- Stage 4: Porewater pH determined by groundwater.

Corrosion Model of Capsule and Disposal Container

The corrosion model of the capsules and containers as implemented in the scoping tool is based on the disposal borehole description (Figures 1) and the available literature data on corrosion of stainless steels. The capsule and container failure times are calculated by the corrosion model, taking into account how the cementitious containment barrier and disposal zone backfill affect the surrounding chemical environment [10,17].

User Inputs of the Scoping Tool and Calculation of Results

The user inputs of the tool are the assessment information, site hydrogeology, site geochemistry, radionuclide inventory, materials and system geometry as shown in Figure 2. After inputting the parameters into the tool with the errors checked, the software would then be run and the results calculated. The calculated results would indicate the degradation times for the backfill and containment barrier cement. The results would also indicate the failure times for the capsules and containers and reasons for the failure.



Site: BDS Site, Ghana
Assessor: Charles Kansaana
Date of Assessment: 28 January 2019
Description (optional):

Figure 2: User inputs of the scoping tool

Radionuclide Decay Calculations

Radionuclide decay calculations were carried out to determine the required time for the nuclides in the DSRSs to decay to their exemption levels by using equation 1.

$$A(t) = A_o e^{-\lambda t} \qquad (1)$$

where A(t) is the activity at any time t, A_o is the initial activity at time t = 0, λ is the decay constant.

Uncertainty Analysis

In order to show the sensitivity of the outcome to the specified inputs, the tool allows the calculation to be repeated for higher values of [Cl^-] and Eh, lower values of pH and both higher and lower values of the groundwater flow and the results retained each time. In total, there are 24 possible calculations [17].

Results and Discussion

The failure times for the capsules, disposal containers, backfill and containment barrier cement for the selected thickness are presented.

Effect of the 3 mm Thickness for Capsule and 6 mm Thickness for Disposal Container for the Reference Design on the Stability of the EBS

For the reference design scenario with the chosen thickness for the capsule and container, the failure/degradation times for the engineered barriers evaluated are shown in Table 7.

Table 7: Failure times for the capsule, disposal container, containment barrier and backfill cement for the reference design thickness: 3 mm for capsule and 6 mm for disposal container

Engineered Barriers Evaluated	Failure Times (in years from time of disposal of DSRSs)			
	Saturated Aerobic Zone		Saturated Anaerobic Zone	
	Start of Failure/Degradation	Completely Failed/Degraded	Start of Failure/Degradation	Completely Failed/Degraded
Backfill Cement	754.8	1888.5	754.8	1888.5
Disposal Container	5198.0 (failure is caused by general corrosion)	5198.0	14548.0 (failure is caused by general corrosion)	14548.0
Containment Barrier	5430.7	5780.2	14781.0	15130.0
Capsule	7575.5 (failure is caused by general corrosion)	7575.5	21540.0 (failure is caused by general corrosion)	21540.0

As indicated in Table 7, the backfill cement would start to degrade at 754.8 years and would have completely degraded after 1888.5 years for both saturated aerobic and anaerobic zones. For the disposal container, it is seen to fail after 5198 years in the saturated aerobic zone and 14548 years in the anaerobic zone. In aerobic condition, it would take 5430.7 years for the containment barrier cement to start to degrade and would have completely degraded after 5780.2 years. Also, the time it would take for the containment barrier in anaerobic condition to start degrading is 14781 years, and would have been completely degraded after 15130 years.

It is observed that the time it would take for the backfill cement to start significant degradation in both aerobic and anaerobic conditions would be the same. Also, the time required for the backfill cement to have completely degraded would also the same for both aerobic and anaerobic conditions. However, the containment barrier cement is seen to degrade at different times under aerobic and anaerobic conditions. These observations could be due to the fact that, the cement degradation model solely depends on the values of the hydrogeological parameters of the site, and it is not impacted by the site's geochemistry unlike the corrosion model. Given that the site hydrogeological parameters are the same for the aerobic and anaerobic conditions, the backfill cement degradation times would be the same for both conditions. The times refer to the backfill cement in the disposal zone as illustrated in Figure 1. The containment barrier cement is observed to have different degradation times for aerobic and anaerobic conditions because the containment barrier is contained inside the stainless-steel disposal container. The container fails at different times for the aerobic and anaerobic cases due to the differing geochemical conditions at the proposed repository site.

The capsule is also seen to fail after 7575.5 and 21540 years in the saturated aerobic and anaerobic zones respectively. It is observed that the capsule recorded the highest value of the failure times in terms of magnitude with the backfill cement recording the least value for both aerobic and anaerobic saturated zones. However, it is observed from the processes that account for the failure times that, it would take much longer time for a disposal container to fail as compared to a waste capsule. Also, it would take many years for the backfill cement to degrade as compared to the containment barrier cement, even though the degradation times of the containment barrier cement are higher than that of the backfill cement.

The time required for the nuclides in the DSRSs to decay to the exemption levels from the radionuclide decay calculations are indicated in Table 8 and Figure 3. The calculations showed that for the radionuclides with relatively short half-lives, it would take 7.03e+02, 5.65e+02 and 1.49e+02 years for the activities of Cs-137, Sr-90 and Co-60 respectively to decay to their exemption levels. For the radionuclides with relatively long half-lives, the required time for the activities of Ra-226, Pu-239 and Am-241 to decay to their exemption levels are 3.19e+04, 2.74e+05 and 8.57e+03 respectively.

The required time for the activities of the DSRSs to decay to their exemption levels are compared to the number of years it would take for the engineered barriers to fail as shown in Table 8. It is observed that, the years it would take for the engineered barriers to fail are above the time required for the activities of Cs-137, Sr-90, Co-60 and Am-241 with relatively short half-lives to decay to the exemption levels, particularly in the case of disposal in the saturated anaerobic zone. This means that the engineered barriers could contain the DSRSs with relatively short half-lives for that period. However, for Ra-226 and Pu-239 with relatively long half-lives; the number of years it would take for the engineered barriers to fail are below the time required for the radionuclides to decay to the exemption levels. This shows that the engineered barriers evaluated appeared not to contain the DSRSs with relatively long half-lives under this scenario.

Table 8: Required time for the nuclides in the DSRSs to decay to the exemption levels

Radionuclide	Initial Activity (Bq)	Exemption Level (Bq)	Time Required for Decay (years)
Cs-137	1.14e+10	1.0e+04	6.04e+02
Sr-90	6.92e+09	1.0e+04	5.65e+02
Co-60	3.37e+10	1.0e+05	9.64e+01
Ra-226	9.93e+09	1.0e+04	3.19e+04
Pu-239	2.70e+07	1.0e+04	2.74e+05
Am-241	8.96e+09	1.0e+04	8.57e+03

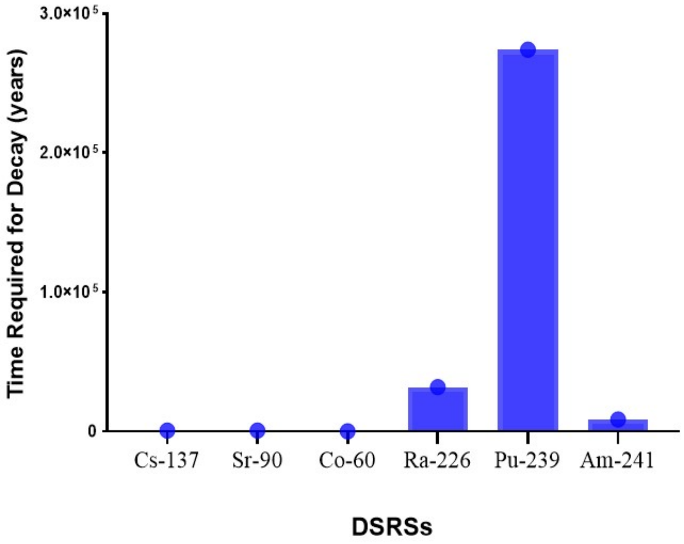


Figure 3: Required time for the nuclides in the DSRSs to decay to their exemption levels

Effect of Reducing the Reference Design Thickness on the Stability of the EBS

In this case, the reference design thickness for the capsule and disposal container was reduced by half, and the failure/degradation times for the EBS evaluated are indicated in Table 9.

Table 9: Failure times for the capsule, disposal container, containment barrier and backfill cement with the reference design thickness reduced by half

Engineered Barriers Evaluated	Failure Times (in years from time of disposal of DSRSs)			
	Saturated Aerobic Zone		Saturated Anaerobic Zone	
	Start of Failure/Degradation	Completely Failed/Degraded	Start of Failure/Degradation	Completely Failed/Degraded
Backfill Cement	773.5	1935.2	773.5	1935.2
Disposal Container	3205.3 (failure is caused by general corrosion)	3205.3	8044.5 (failure is caused by general corrosion)	8044.5
Containment Barrier	3450.9	3819.8	8290.1	8659.0
Capsule	4591.9 (failure is caused by general corrosion)	4591.9	11792.0 (failure is caused by general corrosion)	11792.0

It is observed from Table 9 that if the reference design thickness is reduced, the values of the failure times for the engineered barriers also reduced in terms of magnitude. This shows that the integrity and longevity of these barriers could be compromised if the required thickness is not selected. This means that it would take few years for the engineered barriers to fail and the effect would be that the engineered barriers would become less stable if the reference design thickness is reduced by half.

However, there would be a minimal increase in the failure times of the backfill cement in terms of magnitude as compared to the reference design thickness. This is due to the fact that with reduced thickness of the disposal container, there would be a marginal increase in the corresponding thickness of the disposal zone backfill cement grout. As a result, the number of years it would take for the backfill cement to degrade will be a little much longer as compared to the reference design case.

It is also observed under this scenario that, the number of years it would take for the engineered barriers to fail are above the required time for the relatively short half-lives DSRSs to decay to their exemption levels. For Ra-226 and Pu-239 with relatively long half-lives, the number of years for the engineered barriers to fail are below the required time for the radionuclides to decay to the exemption levels. This indicates that the required time for the engineered barriers to contain the DSRSs is not commensurate with the needed time for the activities of Ra-226 and Pu-239 to decay to the exemption levels.

Effect of Doubling the Reference Design Thickness on the Stability of the EBS

For this scenario, the reference design thickness was doubled, and the failure/degradation times for the engineered barriers are given in Table 10.

Table 10: Failure times for the capsule, disposal container, containment barrier and backfill cement with the reference design thickness doubled

Engineered Barriers Evaluated	Failure Times (in years from time of disposal of DSRSs)			
	Saturated Aerobic Zone		Saturated Anaerobic Zone	
	Start of Failure/Degradation	Completely Failed/Degraded	Start of Failure/Degradation	Completely Failed/Degraded
Backfill Cement	714.5	1787.7	714.5	1787.7
Disposal Container	6146.9 (failure is caused by general corrosion)	6146.9	17740.0 (failure is caused by general corrosion)	17740.0
Containment Barrier	6372.5	6711.4	17965.0	18304.0
Capsule	9018.8 (failure is caused by general corrosion)	9018.8	26353.0 (failure is caused by general corrosion)	26353.0

It is observed from the failure times as indicated in Table 10 that, doubling the thickness of the capsule and container also increased the failure times for both aerobic and anaerobic conditions. As such, it would take more years for the steel barriers to degrade as compared to the reference design thickness and in the event of the thickness being reduced.

However, it is observed from the failure times as stated in Table 10 that, it would take few years for the backfill cement to degrade as compared to the reference design thickness and in the scenario where the thickness is reduced. This could also result from the fact that if the thickness of the disposal container is increased, the corresponding thickness of the cement grout needed to backfill the disposal zone would reduce marginally. As such, the time required for the backfill cement to degrade under this scenario would be less as compared to the reference design case and in the event of the thickness being reduced.

Also, the number of years it would take for the engineered barriers to fail are found to be above the required time for the activities of Cs-137, Sr-90, Co-60 and Am-241 to decay their exemption levels. The engineered barriers in this case would be able to contain the DSRSs excerpt for Ra-226 and Pu-239 with relatively long half-lives. However, there was significant decay in the activity of the long lived DSRSs at the end of the failure times of the engineered barriers, especially for disposal in anaerobic environment. It is therefore observed that, the long-lived radionuclides at the end of the failure times of the engineered barriers would have decayed to low activity levels. Also, the migration of the leached radionuclides would be limited by decay/in-growth, and sorption of the radionuclides onto the cement grout; and as such the activities would have been negligible with insignificant effect. Based on this, the engineered barriers could contain the activities of Ra-226 and Pu-239 with relatively long half-lives to decay to their exemption levels.

The general observation for the three scenarios was that, the difference in the failure times which indicated the stability of the engineered barriers was seen to come from the variations in the thickness of the capsules and disposal containers. Also, the observed variations in the failure times of the engineered barriers followed the order in which the engineered barriers would be conceptually designed to contain the DSRSs as illustrated in Figure 1.

It was also observed that, the failure times would be higher if the DSRSs are to be disposed

in a saturated aerobic environment compared to the saturated anaerobic environment. For all the scenarios, the capsules and containers would fail faster in the aerobic zone when compared to the anaerobic zone. However, the backfill and containment barrier cement would degrade at the same or different times under both conditions. This means that the engineered barriers would fail or degrade faster under aerobic conditions than under anaerobic conditions. In terms of stability therefore, the engineered barriers evaluated would be more stable for disposing the DSRSs under anaerobic conditions as compared to aerobic conditions.

The earlier failure of the engineered barriers under the aerobic conditions could be attributed to the redox potential (oxygen content) of the groundwater at the proposed site. The oxygen content would aid the corrosion and degradation of the engineered barriers since oxygen is required for corrosion to occur [19].

The capsule and container failure in all the scenarios considered was observed to be caused by general corrosion. This could be attributed to the site geochemical values of the pH, Eh and Cl^- concentrations. These values are known to create an environment where general corrosion is most likely to occur on stainless steels [19, 20].

The primary controls on the stability of stainless-steel barriers are the redox potential (O_2 content), pH, Cl^- concentrations and temperature. With decreasing temperature, Cl^- concentration, Eh values and with increasing pH, the stainless steel capsules and containers will have a high level of stability. Cement grout degradation is also accelerated by increasing sulphate concentration, TIC and decreasing pH. Sulphate attacks can have a significant impact on the durability of cement grout [19, 20].

Conclusion

The stability of the engineered barrier system (EBS) of the BDS for the disposal of DSRSs in Ghana had been demonstrated with the aid of a scoping tool. The engineered barriers would fail or degrade faster under aerobic conditions as compared to anaerobic conditions, and consequently would be less stable for disposing the DSRSs in the saturated aerobic zone than in the saturated anaerobic zone. The engineered barriers that would first come into contact with the groundwater in the conceptualised design of the BDS tend to fail much earlier.

The time calculated for the radionuclides to decay to their exemption levels showed that, the engineered barriers appeared stable to contain the DSRSs, especially in the case of disposal in the saturated anaerobic zone for the scenario where the reference design thickness would be doubled. From the demonstration of the results, it can be concluded that the engineered barriers of the BDS evaluated would contain all the DSRSs, particularly in the anaerobic environment for them to decay to their exemption levels.

The results from this study will serve as a useful data for the Nuclear Regulatory Authority (NRA) when granting authorisation to the applicant of the BDS project. The results will also serve as a complementary data for the implementer of the BDS project.

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