SESSION 3a

Disposal of Disused Sealed Radioactive Sources (DSRS)
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IMPLEMENTATION OF THE BOREHOLE DISPOSAL SYSTEM FOR DISUSED SEALED RADIOACTIVE SOURCES IN GHANA

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Abstract. The peaceful application of sealed radioactive sources in Ghana have resulted in the generation of disused radioactive sources that need to be managed in a safe and secure manner. Long term storage which is the practice in Ghana, is considered an unsustainable option for the long lived radionuclide. Hence the need for a suitable disposal option. Ghana Atomic Energy Commission (GAEC) has opted for the IAEA developed Borehole Disposal System (BDS) for the safe disposal of disused sealed sources generated in Ghana. The proposed site for implementation of the BDS is on the GAEC premises at Kwabenya. The site is being characterized to gain a general understanding of the site. The site characterization investigations comprise a number of studies based on geological, hydrogeological, geophysical and hydrochemical methods. The report documents the site characterization activities and the first iteration post-closure radiological safety assessment (PCSA) being carried out for implementation of the BDS in Ghana.

1. Introduction

The over six decades of peaceful application of Sealed Radioactive Sources (SRS) have resulted in the generation of Disused Sealed Radioactive Sources (DSRS). They represent a significant hazard to human health and the environment. They therefore must be managed in a safe and secure manner. The Radioactive Waste Management Centre (RWMC) was established by Ghana Atomic Energy Commission (GAEC) to carry out the safe and secure management of radioactive waste materials generated at GAEC and in Ghana. The RWMC operates a secured Centralised Radioactive Waste Storage facility for characterization and storage of radioactive waste materials.

Storage is an important interim management step, especially for DSRS containing very short-lived radionuclides, which can decay to exemption levels within a few years. However, long-term storage is considered unsustainable option for DSRS with long half-lives radionuclides such as Ra-226, which has a half-life of 1600 years. As Ghana does not have an extensive nuclear power programme that would require the development of a deep geological disposal facility, the GAEC have proposed the International Atomic Energy Agency’s (IAEA’s) developed Borehole disposal Of Spent Sources (BOSS) system for management of the DSRSs. The report discusses the site characterization activities and post-closure radiological safety assessment (PCSA) being carried out for implementation of the borehole disposal system in Ghana.

2. The Borehole Disposal Concept

The BOSS system includes the Borehole Disposal Concept (BDC) which utilizes engineered barriers coupled with intermediate burial depth to provide safe and secure isolation of DSRSs for thousands of years. Safety and protection of human and the environment is achieved through the containment of the radionuclides in stainless steel capsules and
containers and a special concrete grout (the engineered barriers) (fig 1). The small footprint of the borehole and disposal depth supports the realization of the isolation safety and security function.

**FIG. 1: Cross-section through the Disposal Borehole for the Reference Design**

### 3. Site Characterization

The proposed site for implementation of the Borehole Disposal concept is located on the GAEC premises at Kwabenya. The site was being used for the development of radon facilities for storage of DSRS and spent fuel in the early 60’s.

The Dahomeyan supergroup is the major bedrock formation underlying the site and consists of quartzite, gneiss and schists. Geophysical investigation (seismic refraction and electrical resistivity) carried out on the site suggest that the bedrock is probably gneissic or granitic rock. Two boreholes (150 m deep) have been drilled on the site where the high true resistivities were obtained to facilitate the site characterization activities. The groundwater chemistry of the site was characterized by analyses of groundwaters sampled from the boreholes at the site as well as other boreholes located a few kilometers from the site for their chemical and physical parameters. The pH values of groundwater samples ranged from 5.1 to 8.5 indicating that the groundwater ranges from slightly acidic to alkaline condition. The total dissolved solids (TDS) concentration ranged from 125 to 2279 mg/L indicating a variation from fresh to brackish groundwaters [1]. The geochemical environment below the depth of 40m is reducing as demonstrated by the presence of fresh pyrites in the rock formation.

### 4. Post Closure Safety Assessment (PCSA)

Post Closure Safety Assessment (PCSA) is being undertaken using recommendations from the IAEA Improvement of Safety Assessment Methodologies (ISAM)[2,3]. This is to ensure that the assessment is undertaken and documented in a consistent, logical and transparent manner.

Screening calculation was used to identify sources (Co-60, Cs-137, Am-241, Ra-226) which require more detailed consideration in the PCSA. Consistent with IAEA recommendation [4], the PCSA adopted an individual effective dose constraint of 0.3 mSv y⁻¹ for adult members of the public for all potential future exposures other than those arising from human intrusion. The screening process suggested that a total of 26 waste packages will be required for
disposal of the inventory of disused sources, assuming that each source type is disposed in separate capsules/disposal containers.

The scenarios identified in the IAEA Generic Safety Assessment for the borehole disposal concept [5] were reviewed and modified to produce Ghana site-specific scenarios. The main features of the Design Scenario for radionuclides released in the liquid phase into the saturated disposal zones considered discharge via a water abstraction borehole located in a closer proximity to the Borehole Disposal Facility (FIG. 2).

**FIG. 2. Design Scenario: Liquid Releases**

For radionuclides released in the liquid phase, transport from the source container through the various components of the near field can occur by advection, dispersion and diffusion. On leaving the near field, the radionuclides migrate through the geosphere by advection, dispersion and diffusion and are subject to decay/in-growth, and retardation due to sorption onto the rocks. Flow will be through pores and diffusion can occur into stagnant water in the rock matrix.

The assessment results for liquid releases for the design scenario suggests that the plume will arrive at well after 72068 years. In terms of the peak dose an observer is exposed to at the end of the institutional control period from all the radionuclides and their chains is 1.97E-15Sv/y which is lower than the dose criterion of 0.3mSv/y (FIG.3). The dose from all the radionuclides is insignificant hence the radionuclides sources can be disposed of safely in the borehole without posing radiological threat to human and the environment in the future.
FIG. 3. Calculated Dose from the Radionuclides for Anaerobic Porous (Design Scenario).

5. Conclusion

The assessment indicates that Ghana’s current inventory of disused sealed sources appear to be capable of being safely disposed using the borehole disposal system. In terms of biosphere characterization, more site-specific information could be collected. In terms of undertaking the next iteration of the assessment, work would need to be done on; reviewing the corrosion and cement degradation models in light of the determination of the geochemical data (especially Eh and TIC) to be obtained from future site investigations, extending the range of calculations performed (e.g., additional sensitivity cases, consideration of non-human biota, etc.).

REFERENCES


POST-CLOSURE SAFETY OF THE BOREHOLE DISPOSAL CONCEPT

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Abstract. The borehole disposal concept (BDC) was originally developed by NECSA and more recently has been further developed by the IAEA as a safe and secure solution for the disposal of disused sealed radioactive sources (DSRS). The concept is based on disposal in narrow-diameter boreholes at a depth in excess of 30 m. This paper describes the series of iterative, peer-reviewed post-closure safety assessments that have been undertaken over the last 15-20 years to build confidence in the BDC as a safe long-term management option for DSRSs.

Key Words: borehole disposal concept, disused sealed radioactive sources, post-closure safety assessment.

1. Introduction

Many radioactive sources are sealed, with the radioactive materials firmly contained or bound within a suitable housing that is typically a few centimetres in diameter. In some cases, the activity of a source decays to a level below which it is no longer suitable for its original purpose. In others, the associated equipment may become obsolete, worn out or damaged and so can no longer be used. These radioactive sources are referred to as disused sealed radioactive sources (DSRS).

Disused sources may still be sufficiently radioactive to be hazardous to humans and the environment and therefore require careful management; experience shows that loss of control can lead to accidents and even fatalities. In some cases, it is possible to return DSRS to their manufacturer, however, this is not always possible.

For some isotopes, decay storage of DSRS for a few years will be enough for the associated radioactivity to decay to safe levels. For longer-lived isotopes, the source may remain potentially hazardous for hundreds or even thousands of years. For such sources, disposal is the only waste management option providing a safe and secure permanent solution.

Disposal in narrow-diameter boreholes can provide such a safe, permanent and economic solution, especially for those countries without other planned or actual deep repositories. The borehole disposal concept (BDC) was first proposed in 1995 during an IAEA course hosted by the South African Nuclear Energy Corporation (NECSA). Since then borehole disposal of DSRS has evolved from a conceptual idea to a well-defined concept offering an internationally accepted solution for a wide spectrum of DSRSs that can be implemented in a range different conditions. This evolution has been supported by a series of post-closure safety assessments that have investigated the concept’s key safety features, under varying disposal system conditions, to support the concept design and licensing processes and to facilitate its site-specific implementation. This series of assessments are described in this paper.
2. NECSA Post-closure Safety Assessments

A key publication during the first phase of the development of the BDC was [1] which:

- described the concept and its safety objectives;
- provided details of typical DSRS inventories of some African countries;
- defined two generic (illustrative) South African disposal sites to evaluate the concept;
- developed an initial generic design and scenarios to be used in future work.

A preliminary post-closure safety assessment and evaluation of the concept was then carried out and published in 2000 [2]. The assessment considered the disposal of Ra-226 needles at the two illustrative sites. The results showed that the concept met generally accepted safety criteria and it was recommended that further work should be undertaken to develop and refine the concept. As a consequence, a second, generic assessment was undertaken for NECSA for a representative inventory of ten radionuclides and explored a wide range of barriers (stainless steel, copper, lead, cement and bentonite), geospheres (arenaceous, argillaceous and crystalline), and biospheres (humid, seasonally humid and arid/semi-arid) [3]. Following completion this assessment was peer reviewed by an IAEA-convened team of international experts in 2005. The team concluded that the borehole disposal concept was demonstrated to be a safe, economic, practical and permanent means of disposing of DSRS and that it is likely to be applicable for a wide range of DSRS and for a wide range of hydrogeological and climatic environments [4].

3. IAEA Post-closure Safety Assessments

The NECSA assessments were used to inform the subsequent development of a generic post-closure safety assessment for the IAEA (the GSA) which considered an expanded set of 31 radionuclides disposed in a borehole comprising a series of stainless steel and cement barriers [5]. Following an international peer review of the GSA, the models used to evaluate the BDC’s safety were further developed to provide a more detailed representation of stainless steel corrosion and cement degradation under a range of different groundwater flow and chemical conditions.

Figure 1 summarises the two conceptual models used in the GSA where the disposal zone is located (i) in the unsaturated zone, and (ii) in the saturated zone. Both models assume that, after an initial period of containment (the duration of which is dependent upon site characteristics), the disposal packages are breached, resulting in the contamination of groundwater that is then pumped from an extraction borehole and used for drinking and irrigation. In the unsaturated case, rainwater percolates down from the surface, causing released radionuclides to migrate downwards, through the disposal zone and the rock below, into the underlying geosphere. In the saturated case, groundwater moves parallel to the ground surface, leaching released radionuclides from the disposal zone.

The GSA showed that the containment provided by the waste package would be sufficient for most radionuclides to decay to negligible levels. However, for some radionuclides, such as actinides, even the long waste package lifetimes are insufficient to allow them to decay to negligible levels. Nevertheless, the GSA indicated that quantities greater than TBq of the actinides could be accommodated, even if the disposal package was assumed to fail relatively early and hydrogeological conditions at the site were relatively unfavourable.
The GSA’s scope has recently been extended to include the post-closure safety assessment of Category 1 and 2 sources [6]. Calculations have been undertaken to consider the thermal and radiolytic effects of the disposal of high activity Co-60 and Cs-137 sources. The results indicate activity levels that are at the maximum value acceptable from an operational perspective (i.e. around 3000 Ci) would be suitable for disposal using the BDC.


Subsequent to the initial completion of the GSA in 2008, it has provided a useful starting point and worked example for site-specific safety assessments that have been undertaken by a number of Member States from Africa and Asia to evaluate the BDC for the management of their DSRSs (see for example [7]). These assessments have shown that the BDC offers a safe disposal option for each Member State’s DSRSs and, as a result, applications for a licence to construct, operate and close a disposal borehole are currently being prepared in Ghana and Malaysia.

The IAEA has also supported the development of a software tool that can be used by Member States in their country-specific safety assessments (FIG. 2) [8]. It provides them with the capacity to undertake a scoping assessment of one or more potential sites for the BDC. The scoping tool allows rapid decision making by providing an early indication of the potential suitability of site(s) based on site-specific hydrological and geochemical characteristics and the country-specific inventory. It evaluates the containment provided by the waste packages in the post-closure period (through implementing the models developed in the GSA [5]) and has a conservative model of radionuclide transport through the borehole and surrounding geosphere with no retardation of radionuclides. It has been used in assessments in Ghana and Malaysia [7].
FIG. 2. Graphical user interface from the BDC scoping tool showing site geochemistry tab page

REFERENCES


Borehole Disposal of DSRS in Brazil

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Abstract. The safe management of disused sealed radioactive sources (DSRS) is presently a concern of the government of many countries, as well as the IAEA, because many of these sources have potential to cause severe radiological accidents and because a pathway that will eventually lead to their disposal as a radioactive waste is so far mostly unavailable. Brazil is currently one of these countries. The Brazilian inventory of sealed radioactive sources (SRS) includes about 15,630 DSRS, with total estimated activity of 1 PBq stored in centralized waste management facilities and 7,760 SRS still held by the users, with total estimated activity of about 0.2 EBq. When the ²⁴¹Am sources removed from radioactive lightning rods and ionic smoke detectors are included, the number of stored DSRS amounts to about 190,000. The scale and characteristics of the DSRS Brazilian inventory makes their disposal a challenge. An IAEA TCP, in 2014-2015, focused on searching a solution for the DSRS disposal in Brazil. The BOSS concept, developed by NECSA, was evaluated in terms of its feasibility for the Brazilian reality, including inventory, safety and legal considerations and this paper presents the main conclusions.

Key Words: borehole disposal, disused sealed radioactive sources, BOSS concept.

1. Introduction

Brazil has one of the largest inventories of Disused Sealed Radioactive Sources (DSRS) in the world, owing not only to the large industrial activity, the developed infrastructure of medical care and the widespread mining operations, but also due to the use of radiation sources in consumer products, such as radioactive lightning rods, smoke detectors, surge arresters, and even cardiac pacemakers.

Since the early 1980s, DSRS are being safely stored in the radioactive waste departments of the institutes of the Brazilian Nuclear Energy Commission (CNEN) and have been the object of technology development, aiming at completing the steps of their management as radioactive waste, from the design of packaging to the development of final disposal methods.

The policies and provisions on management and disposal of radioactive waste produced in the country are described in the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [1], including the DSRS. Although DSRS are safely stored inside controlled areas and do not pose immediate risk, since they are under a periodic inspection and surveillance program, long term storage is not free from threats. Scenarios of loss of control can be postulated in Brazil as well as in any other country, because DSRS may be the target of theft. Consequently, audits of the security of the DSRS storages should be regularly taken and timely decisions made, as soon as any threat or sign of deterioration in the security are detected.
The final disposal of the DSRS as radioactive waste in a dedicated and exclusive facility in Brazil was acknowledged by those dealing with the management of DSRS in Brazil since the 1990s. Consequently, the Nuclear and Energy Research Institute (IPEN) developed a concept for the disposal of the Brazilian inventory of sources, having a deep borehole with engineered barriers in its core. However, up to this time, the IPEN concept has still a long way to go in terms of detailed engineering, preliminary safety assessment and quality assurance documentation.

During a TCP with the IAEA in 2014-2015 [2], with the participation of staff from other institutes of the Brazilian Nuclear Energy Commission (CNEN), project team chose the BOSS concept developed by NECSA, for further consideration, since the BOSS technology is now ready for implementation, with technical support from the IAEA.

This paper presents the main conclusions achieved during the TCP development about the feasibility of the BOSS concept for the Brazilian reality, including inventory, safety and legal considerations.

2. Brazilian inventory of disused sealed sources

Disused sealed radioactive sources (DSRS) are stored at four nuclear research institutes of CNEN: at Nuclear Technology Development Center (CDTN) – Belo Horizonte, MG; at Nuclear Sciences Regional Center of The Northeast (CRCN-NE) – Recife, PE; Nuclear Engineering Institute (IEN), Rio de Janeiro, RJ and at Nuclear and Energy Research Institute (IPEN) – São Paulo, SP. Table I presents the Brazilian source inventory situation on 31/12/2014.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Radionuclide</th>
<th>Half-life (y)</th>
<th>Activity (Bq)</th>
<th>(%)</th>
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<td>267</td>
<td>Am-241(^{(1)})</td>
<td>432.2</td>
<td>8.3E+12</td>
<td>0.8</td>
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<tr>
<td>105</td>
<td>Am-241-Be(^{(2)})</td>
<td>432.2</td>
<td>8.7E+12</td>
<td>0.9</td>
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<td>8</td>
<td>C-14(^{(3)})</td>
<td>5730</td>
<td>1.6E+07</td>
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<td>15</td>
<td>Cf-252(^{(4)})</td>
<td>2.64</td>
<td>2.8E+08</td>
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<tr>
<td>2,093</td>
<td>Co-60(^{(5)})</td>
<td>5.27</td>
<td>8.6E+14</td>
<td>87.9</td>
</tr>
<tr>
<td>3,098</td>
<td>Cs-137(^{(6)})</td>
<td>30</td>
<td>9.6E+13</td>
<td>9.8</td>
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<td>5,114</td>
<td>Ir-192m(^{2})</td>
<td>241</td>
<td>1.6E+08</td>
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<td>3,429</td>
<td>Ra-226(^{(7)})</td>
<td>1600</td>
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<td>95,454</td>
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<td>4.8E+11</td>
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<td>73,680</td>
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<td>432.2</td>
<td>1.2E+09</td>
<td>&lt;0.05</td>
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<td>4,365</td>
<td>Ra-226(^{(2)})</td>
<td>1600</td>
<td>1.8E+10</td>
<td>&lt;0.05</td>
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<tr>
<td>264</td>
<td>Ra-226(^{(3)})</td>
<td>1600</td>
<td>8.0E+04</td>
<td>&lt;0.05</td>
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<tr>
<td>1,501</td>
<td>Others(^{(1)})</td>
<td>4.7E+12</td>
<td>0.5</td>
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</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>9.8E+14</td>
<td>100</td>
</tr>
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</table>

\(^{(1)}\) Radioactive sources from medical, industrial and research applications
\(^{(2)}\) Radioactive sources attached to lightning rods
\(^{(3)}\) Radioactive sources attached to smoke detectors

The approach for site definition for a borehole repository used for this project is presented in a specific paper “Borehole Disposed of Sealed Sources: Methodological proposal for the site selection of a borehole repository in Brazil” [3].

The preliminary safety assessment developed was strongly based on the generic safety assessment (GSA) performed by Little et al. [4] and IAEA [5] for the borehole repository. For unknown or not yet defined issues (such as site-specific geosphere characteristics), the definitions used in GSA were maintained. For all scenarios calculated in this assessment, including both design and defect scenarios, the results have shown that the only case in which the dose rates exceeded the limit of 0.3 mSv/y was high flow rates in geosphere, with the $^{241}$Am chain responsible for the total dose rate. The impact on the safety assessment results, excluding all $^{241}$Am sources from the present inventory, was also addressed and has shown that the dose rates for all cases were below the dose rate limit.

4. Legal & Regulatory Framework

The Brazilian government through the CNEN, when exercising the powers assigned to it, is responsible for the final disposal of radioactive waste produced in the country. Therefore, CNEN is responsible for the design, construction and operation of radioactive waste disposal facilities as provided for in Federal Radioactive Waste Act of 2001 [6]. In order to enforce the Federal Law the CNEN regulations set up general criteria and basic safety and radiation protection requirements for the licensing of storage and disposal facilities for LILW [7], the Waste Acceptance Criteria of short-lived LILW aiming the disposal of [8] and the siting and site characterization for a short-lived LILW disposal facility [9].

The Brazilian regulation on licensing process of waste facilities also include the waste classification scheme based on IAEA classification [10] indicating the disposal options for each class of the waste. The LILW is classified as Class 2 and subdivided into Class 2.1-Short-lived radioactive waste which must be disposed of in near surface facility and Class 2.4 Long-lived waste whose disposal must be in geological formations with depth defined by the safety assessment.

The regulation gives provisions and specific requirements for step by step of the licensing process including the operational period and the decommissioning program for storage facilities that are designed for managing and storing all classes of LILW (short and long-lived). However, regarding licensing process of the disposal facility (design, construction, operation and closure programs) the national regulation provides specific requirements applicable only to disposal of the Class 2.1-Short-lived waste.

A design and construction of a near surface disposal facility for LILW has been defined as a priority of the National Nuclear Program. However, considering the Brazilian inventory of disused sealed sources many of them may not meet the waste acceptance criteria for near surface disposal in compliance with requirements of Brazilian regulations. The high activity and strength of some specific sources of short-lived radionuclides (i.e. $^{90}$Sr and $^{137}$Cs in order of magnitude of TBq) might not decay to the exemption levels during a conventional institutional control period and therefore they could represent hazard in a near surface repository. Furthermore a large number of long-lived $^{241}$Am sealed sources are of particular concern for disposal of Brazilian inventory since longer half-life sources might require a greater degree of isolation and deeper than the 30 m normally associated with near surface disposal. The depth required for disposal will depend on the host geology of a specific site and the amount of waste to be disposed of.
Therefore, concerning Brazilian regulatory framework, a more specific regulation is required aiming to provide safety requirements for a licensing process applicable to disposal of other classes of waste (e.g. long-lived LILW). All range of activities and radionuclides intrinsic to national inventory of DSRS may require the establishment of further requirements and appropriate approach for their long-term safety disposal and acceptability of other disposal concepts.

REFERENCES


APPLICATION OF IAEA BDC SCOPING TOOL AND AMBER MODELLING IN SAFETY ASSESSMENT OF MALAYSIAN BOREHOLE DISPOSAL FACILITY

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Abstract. IAEA BDC Scoping Tool and AMBER were applied in the post-closure safety assessment of the Malaysian borehole disposal facility for disused sealed radioactive sources. Results obtained from the scoping tool showed that dose limit was exceeded thus indicated that the physical containment provided by the capsule and disposal container was not sufficient to ensure safety of the disposal system for the specified hydrogeological and geochemical conditions and radionuclide inventory. Further assessment was therefore carried out using an assessment model developing in the AMBER assessment tool to evaluate the physical and chemical containment provided by the containment barrier, the borehole backfill and the geosphere. Scenarios considered include Design Scenario, Defect Scenarios (defect of capsule and/or disposal container), Well Scenario and Erosion Scenario. The exposed group receiving the highest dose was identified as farming group for all scenarios except for the Erosion Scenario in which a site dweller group was being considered. Based on the AMBER calculation, the peak dose rate calculated for almost all of the scenarios considered was below the dose limit of 3E-4 Sv y⁻¹ except for the Erosion Scenario with erosion rate 0.01 m y⁻¹. The calculated peak dose rate was reached between approximately 7000 to 400000 years. In all of the calculation cases, long-lived radionuclides in particular americium-²⁴¹ and radium-²²⁶ and their progeny contributed significantly to the calculated peak dose rate.

Key Words: IAEA BDC Scoping Tool; AMBER; Safety assessment; Borehole disposal facility; Disused sealed radioactive sources

1. Introduction

Disused sealed radioactive sources (DSRSs) may have high activity especially those originated from sealed sources used in industrial and medical fields. Some of them may also contain long-lived radionuclides. The DSRSs therefore need to be managed appropriately to ensure the safety of human health and environment. For a non-nuclear power country such as Malaysia, the borehole disposal concept (BDC) is the most viable option for managing this type of waste. The BDC is able to provide a high level of isolation in a cost-effective way. Fig. 1 shows the in situ configuration of a waste package in borehole.

The Malaysian borehole disposal facility (BDF) consists of a 140.25 m deep borehole with an outer diameter of 254 mm capable of accommodating 60 waste packages that over a 60 m disposal zone. An exclusion zone of 10 m to accommodate for an inactive fault is also allocated in the disposal zone. 70 m height is reserved for the closure zone and 0.25 m depth for plugging at the base of the borehole. Both the capsule and disposal container are made of 316L stainless steel.

Prior to the implementation of the BDC, a post-closure radiological safety assessment was carried out to demonstrate and evaluate the safety of the concept to a point of licensability using the generic safety assessment developed by the IAEA as a starting point. As part of the assessment, the IAEA BDC Scoping Tool and the AMBER software tool were used. Migration pathways assessed included the release of radionuclides from the waste packages, migration of the radionuclides via groundwater either to a river (1300 m from the disposal
borehole) or a well and finally use of abstracted water by farmer for drinking and agricultural purposes.

![Diagram of waste package in borehole]

**FIG. 1. In situ configuration of a waste package in borehole**

2. **Calculation Tools**

For the purpose of the safety assessment of the Malaysian BDF, the IAEA BDC Scoping Tool and AMBER were used for undertaking the calculations identified through the use of the assessment methodology described in IAEA (2012).

In the IAEA BDC Scoping Tool, site-specific hydrogeological and geochemical data were used. The radionuclides considered to be disposed were cobalt-60, krypton-85, strontium-90, cesium-137, radium-226, americium-241 and nickel-63. Calculated data on the failure times for the capsule and disposal container, as well as the degradation times for the cement containment barrier and borehole backfill, were further utilized in the AMBER model.

AMBER, a dynamic compartmental model representing migration of radionuclide contaminants from the borehole to the geosphere and finally the biosphere via groundwater, was used to represent the disposal system. Site-specific conditions were represented in the AMBER model with the generic information from NECSA (2004) being used in the absence of site-specific data. Based on geological data from the proposed site, the disposal borehole was assumed to be located in the saturated zone under aerobic conditions. In order to assess the safety of the disposal system, a number of scenarios were identified including Design Scenario, Defect Scenarios, Well Scenario and Erosion Scenario. The Design Scenario was developed to represent the evolution of the disposal system when the borehole was implemented as designed and functioned as expected. It provides a benchmark against which other scenarios can be compared. In the Defect Scenarios, it was assumed that the capsule and/or disposal container do not perform as envisaged in the Design Scenario. In the Well Scenario, the geosphere-biosphere interface (GBI) considered was a water abstraction well instead of a river (as was considered in Design Scenario) located at certain distances from the disposal borehole. In the Erosion Scenario, it was assumed that the disposal zone would be uncovered after a certain period of time and radionuclides would be released to the biosphere. For the Defect Scenario that assumed a defective capsule is placed within a defective disposal...
container, variant calculations were also carried out for 30 and 60 defective waste packages. For this particular Defect Scenario and its variants, it was assumed, consistent with [1], that 10% of the waste in each defective waste package was available for release from the time of emplacement until the time that the capsule totally fails. Assessment endpoint was discussed in terms of radiological doses to farmers (Design Scenario, Defect Scenarios, Well Scenario) and site dwellers (Erosion Scenario).

3. Results and Discussion

Simulation results presented in Table 1 are based on the Malaysian BDF modelled using AMBER.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Calculated peak dose rate, Sv y(^{-1})</th>
<th>Time of calculated peak dose rate, y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>3.6E-12</td>
<td>4.2E+5</td>
</tr>
<tr>
<td>Defect</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 defective disposal container containing an intact capsule</td>
<td>3.6E-12</td>
<td>4.2E+5</td>
</tr>
<tr>
<td>1 defective capsule in an intact disposal container</td>
<td>3.6E-12</td>
<td>4.2E+5</td>
</tr>
<tr>
<td>1 defective waste package</td>
<td>3.6E-12</td>
<td>4.2E+5</td>
</tr>
<tr>
<td>30 defective waste packages</td>
<td>3.6E-12</td>
<td>4.1E+5</td>
</tr>
<tr>
<td>60 defective waste packages</td>
<td>3.6E-12</td>
<td>4.1E+5</td>
</tr>
<tr>
<td>Well</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10m from disposal borehole</td>
<td>3.2E-4</td>
<td>1.3E+4</td>
</tr>
<tr>
<td>20m from disposal borehole</td>
<td>9.6E-5</td>
<td>1.4E+4</td>
</tr>
<tr>
<td>30m from disposal borehole</td>
<td>4.1E-5</td>
<td>1.5E+4</td>
</tr>
<tr>
<td>40m from disposal borehole</td>
<td>2.0E-5</td>
<td>1.6E+4</td>
</tr>
<tr>
<td>50m from disposal borehole</td>
<td>1.1E-5</td>
<td>1.6E+4</td>
</tr>
<tr>
<td>100m from disposal borehole</td>
<td>1.3E-6</td>
<td>1.8E+4</td>
</tr>
<tr>
<td>500m from disposal borehole</td>
<td>2.7E-8</td>
<td>1.7E+5</td>
</tr>
<tr>
<td>Erosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erosion rate = 0.001 m y(^{-1})</td>
<td>2.5E-6</td>
<td>7.0E+4</td>
</tr>
<tr>
<td>Erosion rate = 0.01 m y(^{-1})</td>
<td>2.3E-3</td>
<td>7.0E+3</td>
</tr>
</tbody>
</table>

Results obtained showed that for the Design and Defect Scenarios, the calculated maximum dose rate received by farmer was 3.6E-12 Sv y\(^{-1}\) (well below the dose limit of 3E-4 Sv y\(^{-1}\)) and occurred after approximately 400000 years. The similarity in the dose rate was due to the fact that calculated peak doses are dominated by Am-241 progeny that ingrow in the disposal system (be it the waste package or the geosphere). Due to the long travel time to the GBI and associated attenuation in the geosphere, the results are relatively insensitive to precise timing of the failure of the waste package given that both scenarios assume total failure has occurred before 5000 years.

In the Well Scenario, the peak dose rate was lower that the dose limit except for the well located 10m from the disposal borehole (it is very unlikely that a water abstraction well is drilled at that distance). The time at which the calculated peak dose occurred increased with distance from the disposal borehole, while its magnitude decreased due to the increased travel time of radionuclides to the well.

In the Erosion Scenario, as the erosion rate increases from 0.001 m y\(^{-1}\) to 0.01 m y\(^{-1}\), the peak dose rate also increased from 2.5E-6 Sv y\(^{-1}\) to 2.3E-3 Sv y\(^{-1}\). The time at which the calculated
peak dose occurs was 70000 and 7000 years respectively. The peak dose rate received by the site dweller was mainly derived from Ra-226 and Am-241 and/or their progeny.

4. Conclusion

The IAEA BDC Scoping Tool indicates that the physical containment provided by the capsule and disposal container is not sufficient to ensure safety of the disposal system for the specified hydrogeological and geochemical conditions and radionuclide inventory. More detailed modelling using the AMBER software tool indicate that the BDF would be effective in providing safe solution for the disposal of both long-lived and short-lived radionuclides in most of the scenarios considered. In the scenarios where the dose limit $3E-4 \text{ Sv y}^{-1}$ is exceeded, the likelihood of the occurrence of such scenarios is very low.

5. Acknowledgement

The authors would like to extend their gratitute to the team members of the Borehole for Disused Sealed Radioactive Sources (BOSS) Project from Nuclear Malaysia. The authors would also like to thank Mr Richard Little from Quintessa Limited for sharing his knowledge, expertise and experience as well as unlimited support in assisting Nuclear Malaysia to undertake the AMBER modelling. Special thanks are also dedicated to the IAEA for their financial and expertise support in this project.

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Abstract. The adequate management of disused sealed radioactive sources (DSRS) is an important problem associated to its widespread generation from the nuclear applications and the high level activities for some DSRS on this specific wastes stream. The Borehole Design Concept (BDC) has been evaluated as feasible disposal solution to avoid the high costs linked to the implementation of the deep geological options. In this paper the results of the tool application (screening tool) for safety assessment to estimate the impact of the DSRS disposal from the nuclear program in Cuba using the BDC, are shown. The preliminary assessment was supported by the information associated to the facility design, site characterization results (mainly hydrogeology and geochemistry) and the DSRS inventories. Supported by the site documentation, also was studied the data variation to evaluate the role played for some parameters uncertainties on the estimated radiological impact. The outputs showed that the impacts were below to the target dose limit for both evaluated pathways; well water and house dweller. The radiological impacts are different for the evaluated scenarios and the higher doses are related to well water scenario. Also, the main radionuclides according its contribution to the final dose for the critical groups were identified. These preliminary results are relevant to support the planned next stages; definition of the waste acceptance criteria for the disposal facility and the radiological assessment for the predisposal operations.

Key Words: borehole, safety assessment, sealed sources, screening tool.

1. Introduction

The final management of the radioactive wastes should provide solutions that fulfill the regulatory requirements on radiation protection, nuclear safety, etc. The nuclear programme in Cuba generates radioactive wastes coming from the nuclear applications, fundamentally associated to the medicine, research and the industry. Among these wastes the disused sealed radioactive sources. According the above mentioned characteristics the DSRS cannot disposal in facilities for low activity radioactive wastes, therefore is a problem its management in countries with limited nuclear programme.

The Borehole disposal concept (BDC) is a engineered system which allows the safe and permanent disposal of DSRS in specially created boreholes [1], see figure 1. This system has been designed to provide a safe, economic, simple and permanent solution for the long term management of DSRS. Different studies about the BDC [1, 2] have been showed its advantages to ensure the final disposal of DSRS. In this paper the results for a preliminary safety assessment for DSRS disposal in a Cuba site are showed.
2. Materials and methods

For this study was applied the Safety Assessment Methodology [3] which included all relevant elements related to safety assessment and safety case. Also, the preliminary safety assessment was carried out using the IAEA BDC Screening tool version 1.1 a computer program to evaluate the potential sites for BDC [2]. These softwares have been developed in the framework of IAEA and others International Projects [2,4].

The inventory of DSRS were obtained from the Cuba Country Report 2010. The site data was provided by the results of site selection process carried out in the country until the site characterization stage [6]. The selected site is placed in the central part of the country and the geology is associated to granodiorites belt, see figure 2. The area is located in a tectonically stable block surrounded with agriculture and livestock developments. The limited groundwaters presence in the site is associated to surface fractures in the rock.

The BDC is a relevant part of the radioactive waste disposal system. This facility includes different engineered barriers to ensure the safety of DSRS disposal [1]. The DSRS are placed in one borehole, with 60 stainless steel capsules and disposal containers, also liners and backfill materials as barriers to avoid or reduce the radionuclides release are included. For this preliminary safety assessment all features have been kept similar to the BDC original design.

The screening tool, see figure 3 was applied to carry out a Generic Safety Assessment (GSA) in the post-closure period for the BDC. This software includes conservative models and it is useful to evaluate site suitability at preliminary stages [2].
FIG. 3. Initial screen of BDC tool

The main user inputs for the BDC tool are the radionuclides inventory, the site hydrology and geochemistry. The DSRS inventory from nuclear applications is showed in the figure 4.

FIG. 4. Radionuclides activities

The hydrology and geochemistry parameters adopted in the GSA for the saturated zone were: hydraulic conductivity (0.3 m/y) and gradient (0.028), porosity (0.3), pH (8), Eh (-235 mV), concentration of Chloride and Sulphate, 45 and 23 mg/L respectively. For the unsaturated zone the parameters were; percolation rate (0.168 m/y), degree of saturation (0.1) and the total porosity (0.2). The BDC tool supports the uncertainties analysis through the modification of several parameters (pH, Eh, Chloride and groundwater velocity), these values were selected according the site studies focused in the behavior of the hydrogeology and geochemistry [5].

The water well and house exposure scenarios were evaluated in the GSA. For the water well scenario the rainwater percolate down causing the wastes migration from the disposal zone to the aquifer. The contaminated water is collected for drinking in a water extraction well at 100 distance. The final dose to the target group living on the site is evaluated. In the house exposure scenario a house construction above the disposal borehole at the end of the institutional control period (30 years) is assumed. The exposure dose associated to the gas released from the BDC for an adult resident is assessed. The assessment endpoint define to evaluate the radiological impact was the dose constraint of 0.3 mSv/y. The models included in the BDC tool take into account the barriers degradation process [1] additionally.
3. Results

For the water well scenario the total peak dose was \(3.7 \times 10^{-4}\) mSv/y at \(7.24 \times 10^5\) years (peak time), this dose is below the dose constraint. The radionuclides impacts are showed in the figure 5. The main radionuclides are; \(^{210}\)Po, \(^{210}\)Pb, \(^{229}\)Th and \(^{226}\)Ra and their relevance is associated to the role played by its characteristics; half-life, activity and long-lived daughters.

![Dose impacts vs Rns](image)

**FIG.5. Dose impacts for the water well scenario.**

For the house exposure scenario the dose peak is \(6.1 \times 10^{-7}\) mSv/y at \(7.20 \times 10^5\) years linked to \(^{222}\)Rn only. The estimated failures times (cement barriers) varies from \(3.24 \times 10^4\) to \(5.7 \times 10^4\) years and for the containers and capsules are \(4.8 \times 10^5\) years and \(7.2 \times 10^5\) years respectively.

The results for the preliminary GSA are associated to the favorable characteristics of the site (geology, geochemistry and hydrogeology). The estimated doses are essentially affected by the wastes travel time to the well and barrier degradation processes, these factors are positive impacted by the granodiorite host rock and the poor groundwater conditions. The uncertainties analysis not showed impacts in the total dose peak for both scenarios. Preliminary, the selected site is favorable to support the disposal of DSRS using the BDC. In next stages for a detailed post-closure safety assessment the accidental and altered evolution scenarios should be evaluated. Also, more specific and less conservative models should be applied.

4. Conclusions and recommendations

- According the GSA results the containment provided by the BDC is sufficient to ensure the safety of the DSRS disposal in the evaluated site.
- The relevant radionuclides on the radiological impact for both scenarios were identified.
- In next stages, other potential scenarios and models should be evaluated for a detailed post-closure safety assessment.

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Borehole Disposed of Sealed Sources
Methodological Proposal for the Site Selection of a Borehole Repository in Brazil

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Abstract. According to the Brazilian regulation for site selection for low level waste repositories, areas of interest and preliminary areas steps must encompass a bibliographic review, followed by a systematic study of natural characteristics and infrastructure. Using a GIS platform, a methodology based on spatial and geochemical/hydrochemical databases for porous and fissural domains, along with selection/exclusion criteria, were proposed to select possible sites of a borehole repository for sealed sources. After this selection, technical, logistical and juridical features were also considered. Applying this methodology for Brazil, 209 counties were selected as preliminary areas. The lack of necessary databases can be a difficult for applying this approach.

Key Words: disused sealed sources, borehole repository, site selection

1. Introduction

Site selection for a borehole repository is one of the key components of site assessment. Together with engineered barriers, the site must provide radiological protection, meeting all the requirements established by the regulatory bodies [1]. This paper proposes a methodology for selection of preliminary areas for borehole repositories using geoprocessing tools and applied for a Brazilian case, by means of public domain databases.

2. Methodology

This work follows the three-stage methodology proposed by [2]: concept and planning, area survey and site characterization, focusing only on the first and second stages.

Using GIS tools, the desirable features described for each attribute related to the available databases were selected. Considering the type of featured data, databases comprise Terrain Features (geology, hydrogeology and geochemistry/hydrochemistry) and Technical, Logistical and Juridical Features, also named TLJ (distance to source cities, indigenous areas, main drainages, environmental conservation unities, mining areas, high altitude areas and highways, and a maximum limit for demographic density). For each database, the key criteria and desirable characteristics for best overall performance of the repository were selected, based on [2], [3] and [4]. The interception of the results of the several considered characteristics resulted on a list of possibly suitable areas.

Due to the natural differences in the hydrodynamic behavior of groundwater pathway, groundwater evaluation in terrain features was divided in fissural and porous approaches. Each approach generated partial results, which were evaluated after by TLJ aspects (man-induced aspects, in accordance to [5]).

Geochemical characteristics of the water at the near field play an important role in the behavior of engineered barriers, since they are subjected to corrosion and degradation through the interaction with water and geological environment. Although there are no guidelines for the limit values for hydrochemical parameters for a best performance of the
engineering barriers, a range of values was established based on geochemical characteristics of the Water Sample no. 5 [6] for pH (>8.46) and sulphate concentration (<10.66 mg/L) and on the Water no. 6 [6] for chloride concentration (<100 mg/L). For this evaluation, it was used geochemical database available in [7]. Water boreholes were chosen when they were within 1 km from the areas selected from the preliminary results (evaluation of fissural and porous sites).

The simplified workflow for site selection methodology is presented below (FIG. 1.)

FIG. 1. Simplified workflow for site selection methodology

3. Results of the selection process

The intersection of the results obtained by successive rounds of analysis through the Fissural Approach (geodiversity [8], lithology [9], hydrogeology [10] and geochemistry/hydrogeochemistry [11]) is presented in FIG. 2.

For the Porous Approach, it was adopted the following databases: hydrogeological, geodiversity, geochemistry/hydrogeochemistry. Numerical data for the hydrodynamic characteristics of porous aquifers are available in the hydrogeological database, making it be more relevant in the analysis compared with the fissural approach. Geodiversity database was used with the same criteria adopted for the fissural approach. The results intersection is presented in FIG. 3.

For the geochemical/hydrogeochemical feature, none of the available water borehole data were located close enough to the already selected sites to add any further information to the suitability of the site selection.

For the TLJ features, six criteria were defined: distance to source cities, to indigenous areas, to main drainages, to environmental conservation unities, mining areas and maximum limit for demographic density. These criteria were selected based on having the largest impact of land use, database availability and compliance to the aspects determined by [12]. For each threshold parameter, an area of inclusion or exclusion was defined with the same methodology applied to the site selection (Sensibility Tests) of the Brazilian Low and Intermediate Levels Waste Repository Project (RBMN Project) presented on [13]. Result of
this analysis is shown in FIG. 4), and the final results including all the criteria are shown in FIG. 5.

FIG. 2. Results for the Fissural Approach

FIG. 3. Results for the Porous Approach

FIG. 4. Results for the TLJ Evaluation process

FIG. 5. Final results for Preliminary Areas

4. Conclusions and final remarks

The evaluation lead to a list of 209 counties that contains areas that met the requirements according to the methodology proposed. The site selection using geospatial analysis from multiple databases was able to provide significant results especially due to the possibility of correlating different variables and parameters. However, the results must be treated with precaution due to the tendency of rejecting sites based on false premises as the result of lack of appropriate databases, heterogeneous scales of the databases, eventual data inconsistencies and subjectivity of some criteria and/or numerical parameters.

Ultimately, as result of the robustness of the engineering barriers of the BOSS concept, it is worth considering that accordingly to well stablished in the reference literature [14] only few requirements for the site must be satisfied, mainly related to hydrogeological and geochemical conditions.

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