SAND2017-13052C

International Implementation of IAEA's Borehole Disposal Concept for Sealed Radioactive Sources – 18545

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ABSTRACT

With funding from the Government of Canada, and support from the U.S. Nuclear Regulatory Commission's (NRC's) Office of International Program and many others, the International Atomic Energy Agency (IAEA) is supporting the field deployment of the Borehole Disposal Concept (BDC) for secure disposal of radioactive sources in Ghana, the Philippines and Malaysia. This is a first-of-its-kind implementation.

Though small in volume, disused sealed radioactive sources can be intensively radioactive and create a significant safety and security liability for the majority of the 168 Member States in the IAEA. Millions of sealed radioactive sources have been manufactured since 1901, and it is estimated that hundreds of thousands are now unwanted. The irony is that some of the countries with the smallest inventories have the greatest difficulties managing their radioactive wastes.

The BDC was originally conceptualized in an IAEA-study undertaken by the South African Nuclear Energy Corporation (NECSA) for countries with small inventories of disused sealed radioactive sources. There are multiple, passive engineered and natural barriers in the BDC design, including an inner stainless-steel capsule (which holds the wastes), an inner cement containment barrier, an outer stainless-steel container and outer backfill cement, as well as the surrounding geosphere. In common subsurface geochemical environments, these barriers will isolate the wastes from the biosphere, provide effective containment and ensure long-term safety. To greatly limit the likelihood of inadvertent human intrusion (safety), and advertent human intrusion (security), these waste packages will be disposed of in a narrow-diameter borehole (26 cm) at depths greater than 30 m. Borehole disposal creates an exceptionally small footprint, removes the wastes from normal human surficial activities, and isolates the waste packages from near-surface processes.

Over the past 20 years, the IAEA, NECSA and many others have advanced the BDC on the shoulders of the IAEA's broader work supporting safe and secure disposal of radioactive wastes and management of sealed radioactive sources. Now, with funding from Global Affairs Canada, and support from the U.S. NRC and many others, the IAEA has assisted Ghana, Malaysia and the Philippines in assessing their inventories and conditioning their disused sealed radioactive sources, in drilling investigation boreholes and characterizing their proposed sites, and in designing their disposal systems. These countries plan to place the upper-most waste package at depths greater than 100 m. While activities in the Philippines remain focused on site characterization, Ghana and Malaysia are each in the latter stages of developing their Safety Case for operational and "post-closure" safety. These Safety Case Reports will be an important component of their respective license applications.

Though this paper identifies the support provided to Member States by the IAEA, it is the Ghana Atomic Energy Commission and the Malaysian Nuclear Agency that are responsible for the safety of the disposals and that have been responsible for carrying-out their disposal programs. Once the BDC is licensed by the relevant national regulatory bodies, these first-of-a-kind disposal activities will provide a template for other countries to safely dispose of their disused sealed radioactive sources – permanently eliminating their safety and security liabilities.

INTRODUCTION

Rich or poor, developed or developing, essentially every country in the world produces radioactive wastes, and for the majority of those countries, the most difficult of those radioactive wastes to manage are the disused sealed radioactive sources (DSRSs). With a wide range of beneficial applications, over 10 million sealed radioactive sources (SRSs) have been manufactured over the past century, and now millions are considered "disused," and of those, the majority are being managed as radioactive waste.

Physically small, and sometimes radioactively-potent, these DSRSs are recognized as both a safety threat from poor management and accidents and a security threat from possible use in malevolent acts. Today, the vast majority of these DSRSs are in storage; although it is not possible to store long-lived DSRSs until radioactive decay renders the sources harmless. Disposal is the only viable, long-term solution for the predominance of the DSRSs. But disposal has been difficult and, as examples, the authors are not aware of any disposal facilities for DSRSs in the Middle East or in Africa. Even in the United States (U.S.), higher activity DSRSs are being held in storage due to a lack of disposal options.

Given the shortage of disposal facilities for DSRSs, an important initiative of the International Atomic Energy Agency (IAEA) has been to develop an integrated program that supports the efforts of Member States to manage and dispose of DSRSs. This program includes development of a mobile hot cell and the IAEA's Borehole Disposal Concept (BDC), which is a multi-barrier disposal system for DSRSs that places waste packages at depths greater than 30 m in a narrow-diameter (26 cm) borehole.

Over the past 15 years, Ghana, Malaysia, the Philippines and other countries have requested international assistance in implementing the BDC. Today, with Canadian funding, the IAEA and other national organizations are fielding a program that is implementing the BDC for DSRSs – a first ever accomplishment. This paper provides an overview of the nature of DSRSs, the safety and security threat they pose, the long-term management options, development of the BDC and progress in its first ever implementation by Ghana and Malaysia.

WHAT ARE SEALED RADIOACTIVE SOURCES?

A SRS is simply a small container of radioactive material that is sealed to contain the radioactive material, but not the radiation; because it is the radiation that is harnessed for beneficial purposes. SRSs typically appear as small pieces of metal (see Figure 1), with the majority of the SRSs being less than 15 cm^3 and the largest military and industrial SRSs being less than 280 cm^3. Sealed radioactive sources were first manufactured in 1901 using naturally-occurring radium-226 (Ra-226), and only naturally-occurring nuclides were used until the advent of nuclear reactors in the 1940s.

Fig. 1. Low Energy Gamma Sources (Photo credit: QSA Global)

In many cases, SRSs are used in beneficial applications that would otherwise be difficult or impossible. In medicine, radiation is an indispensable tool used to treat about half of all cancer patients. Sealed radioactive sources are also used to sterilize blood, to batch-sterilize medical equipment, to target cancerous tissue using calibrated radiation beams, and in other applications, the SRSs allow measurements of properties that could not otherwise be measured (e.g., in logging oil and gas wells and verifying the welding of pipelines). Sealed radioactive sources are used daily and worldwide in manufacturing, consumer products, construction, oil and gas exploration, research, space exploration, teaching, and military applications. Sealed radioactive sources can be found in nearly all countries, and in the U.S. they can be found in places ranging from home smoke detectors, to university research laboratories to medical clinics.

Technically, a "radioactive source" means radioactive material that is permanently sealed in a capsule or closely bonded, in a solid form and which is not exempt from regulatory control [1]." Specially manufactured pieces of activated metal, such as Cobalt-60 (Co-60) or Iridium-192 (Ir-192), are also SRSs. Since the 1940's, SRSs have been manufactured to contain materials that can produce alpha radiation, beta radiation, gamma radiation and even neutron radiation. Half-lives of isotopes commonly used in SRSs vary from 74 days for Ir-192 to 1,600 years for Ra-226.

Fig. 2.Disused Medical "Source Devices" that Contain High-Activity DSRSs

Few products are as diverse as SRSs, with activity levels ranging over nine orders of magnitude. The very lowest activity SRSs require minimal shielding (e.g., the SRS in a home smoke detector) and the highest activity SRSs that may require >1,000 kg of metal shielding. Figure 2 shows disused medical equipment that contains heavily-shielded DSRSs.

Because of their widespread beneficial applications, *more than ten million SRSs have been manufactured* [2].

SAFETY AND SECURITY THREAT

Sealed radioactive sources appear harmless - because human senses cannot detect the radiation. From a safety perspective, fatal accidents have occurred when a farmer or a construction worker brings home a small, interesting piece of metal from a poorly controlled work site. Even the name can be misleading; if the sources are "sealed," it is often assumed that they are safe.

There were profound changes following 9/11 and safety and security experts became increasingly concerned that SRSs or DSRSs could be used in a radiological dispersal device (RDD) or so-called dirty-bomb. The concerns of security experts (and safety experts) are exemplified by a 1987 accident in Goiânia, Brazil, where a 50-terabecquerel (TBq) (1350 Curie (Ci)) Cesium-137 (Cs-137) source was stolen by two scrap metal collectors from an abandoned medical clinic and cut open. The resulting radioactive contamination was both invisible and frightening. Four people died from the acute radiation exposure; several hundred suffered health effects, acute anxiety ensued, and emergency services were overwhelmed by 112,000 people seeking medical attention [3]. Several years were required to decontaminate or demolish buildings and remove contaminated soils, generating thousands of cubic meters of radioactive wastes. There was discrimination against both people and products from Goiânia with a 20% decrease in the sales of manufactured goods and a dramatic decline in tourism [4].

Today, the consequences of an RDD attack in a seaport, airport or population center could be very costly, taking into account the emergency response, evacuation, medical response, radiological assessment, decontamination or demolishment of facilities and lands, radioactive waste management and disposal, rebuilding, and loss-of-use. There would also be intense international news coverage – with negative consequences for the nuclear community. Though over 15 years have passed since 9/11, the radiological security threat remains largely "undiminished" [5]. The repercussions from the Fukushima nuclear disaster following the 2011 tsunami in Japan also illustrate this point.

Because of low source strength and non-dispersible source forms, most *individual* SRSs and DSRs do not pose a RDD risk. The IAEA has developed a categorization system, based on the immediate hazard; which allows a graded approach in the application of safety measures for managing sealed sources. The IAEA categorization divides sealed sources into five categories. Category 1 and 2 sealed sources are the most dangerous and Category 5sources are the least dangerous. A few minutes exposure to an unshielded Category 1 source can cause death. [1] The greatest RDD risk is from the Category 1 and 2 sources, and for that reason priority is given to these sources from a security and safety point of view.

A SRS that is no longer useful is especially vulnerable, because it may be a burden to its owner and is potentially subject to less rigorous controls. A previous study defines a "*dangerous and vulnerable SRS*" as a Category 1 or Category 2, unwanted SRS (i.e., a SRS that cannot be recycled or returned) [6]. For example, the contamination incident in Goiânia, Brazil involved a dangerous and vulnerable SRS (i.e., an unwanted Category 1SRS).

So called "orphan sources" pose a particular problem in many countries, as their ownership, management and even location may be unknown and consequently there is no possibility of regulatory control until they are found and secured. The reasons why SRSs become orphan source are numerous, including: a weak regulatory infrastructure, abandonment, loss, theft or transfer of ownership without authorization. The IAEA has initiated many missions in Member States to identify and retrieve such orphan sources. Continuous training courses are presented by the IAEA and other countries such as the U.S. to train Member States in the search and recovery of orphan sources.

After 9/11, Canada, the European Union, France, the U.S. and many others increased their efforts to reduce the security threat posed by sealed sources. In 2002, the "Group of Eight" (G8) launched the *Global Partnership Against the Spread of Weapons and Materials of Mass Destruction* (Global Partnership), which pledged $20 billion U.S dollars over ten years to address threats in Russia and the former Soviet Union. The Global Partnership was extended in 2013; its scope expanded to address threats around the world, and currently includes contributions from 30 states and the European Union.

The IAEA, an autonomous United Nations (UN) agency that reports to the UN General Assembly and the Security Council, has undertaken many activities to enhance nuclear and radiological security to mitigate the threat of nuclear terrorism through strengthening the capabilities of its Member States. With 168 Member States and staff from over 100 countries, the IAEA has been concerned about the safety of SRSs and DSRSs for decades and has produced many documents to assist their Member States (listed later). Significant work completed by the IAEA after 9/11 includes the development of the *Code of Conduct on the Safety and Security of Radioactive Sources* [1] to help national authorities in Member States ensure that there is an appropriate regulatory framework for the safe and secure management of SRSs and DSRSs. This has been augmented by the recently-approved *Supplementary Guidance on the Import and Export of Radioactive Sources*, which introduces additional recommendation on how to enhance the security of SRSs [7].

DSRS AND MANAGEMENT OPTIONS

All SRSs have a service lifespan and become "disused;" either because of radioactive decay or because the equipment holding the SRS has become obsolete, worn-out or damaged. "A radioactive source which is no longer used and is not intended to be used for the practice for which an authorization has been granted" is a DSRS [1]. Up to 25% of all SRSs are now DSRSs ([8] NEED CITATION). In total, there may be several million DSRSs in the world. Nearly all countries have SRSs and must manage DSRSs. The management options for these DSRSs are:

1. Decay in storage
2. Reuse or Recycling
3. Return to the vendor/repatriation
4. Storage and
5. Disposal.

The DSRSs that contain *very short-lived* nuclides (such as Ir-192) can be decayed in storage; however, only a small percentage of all DSRSs contain very short-lived nuclides. Reuse in another application, and recycling in the same application are appealing, but reused and recycling are typically impractical or uneconomical, except for the highest-activity DSRSs (which are most economically-viable for reuse or recycle). Developing countries lack the trained personnel and facilities necessary to characterize, recertify and reuse or recycle DSRSs. The irony is that some of the countries with the smallest inventories have the greatest difficulties managing their radioactive wastes.

In some cases, a DSRS can be returned to the manufacturer – but such opportunities are limited because: older DSRSs may not meet current encapsulation standards; manufacturers may have gone out of business; there may be no "special form" shipping certification, and shipping to the manufacturer may be too costly, or it may be less expensive to manufacture new materials than to recycle old materials. In certain cases, a DSRS may be "repatriated" to the country of origin. Figure 3 shows the repatriation of Co-60 source devices to the U.S. The cumulative cost was significant for the planning, security, technical experts, intermodal transport and disposition in the U.S.

Today, the vast majority of DSRSs are in storage at the user's facility or a government facility. Unfortunately, it is not possible to store all DSRSs until radioactive decay renders the sources harmless. Figure 4 shows the time required for DSRSs to decay to IAEA exemption levels. For example, approximately 1,000 years of storage will be required for commonly-used Cs-137 sources to decay to safe levels. It is difficult to imagine maintaining active control over a storage facility for wastes for a millennia. Safe, secure storage is a critical, but interim step.

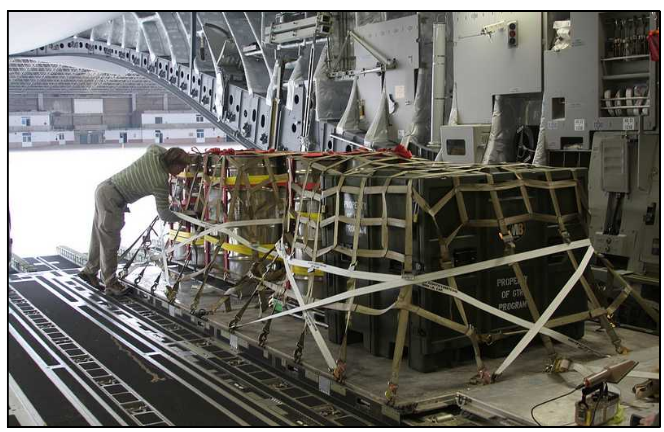

Fig. 3. Repatriation of DSRSs

Disposal is the only viable, long-term solution for most DSRSs. Unfortunately, only a few countries have disposal facilities for radioactive DSRSs. For example, the authors are not aware of any disposal facilities for DSRSs in the Middle East or in Africa. Even in the U.S., higher activity DSRSs are being held in storage due to a lack of disposal options. In the Middle East, and in most regions of the world, DSRSs are being held in storage.

In the U.S., with a robust radioactive waste management infrastructure, there are disposal facilities for most low-activity DSRSs, and in high priority cases, the U.S. Department of Energy National Nuclear

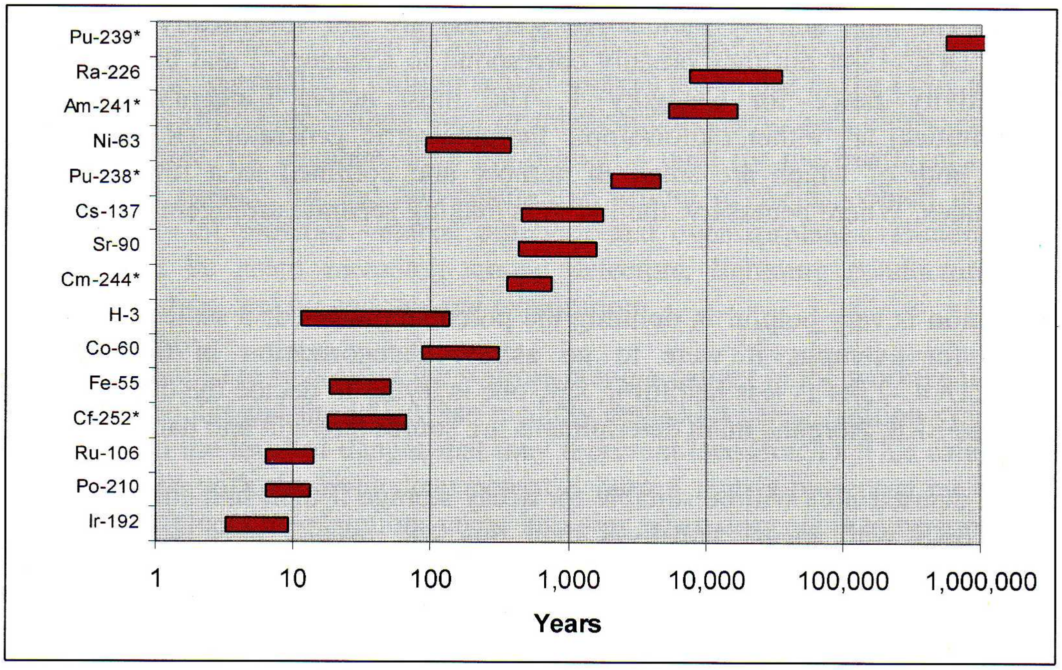

Fig. 4. Time Required for Nuclides in DSRSs to Decay to the IAEA's Exemption Levels (Asterisk Indicates Nuclides Where Progeny Are Longer-Lived than the Parent Nuclide) [2]

Security Administration's (DOE/NNSA's) Off-site Source Recovery Project will recover and store unwanted higher-activity DSRSs (http://osrp.lanl.gov/). However, even in the U.S., there are no licensed disposal facilities for higher-activity DSRSs (e.g., there are no disposal facilities for Cs-137 DSRSs that exceed 4.8 TBq (130 Ci) [9]. Therefore, even in the U.S. there is no disposal facility that can accept a Cs-137 DSRS of the same strength as the source in the Goiânia, Brazil accident. Co-disposal of DSRSs with high-level radioactive waste and/or spent nuclear fuel has been proposed in the U.S. and other countries with nuclear power programs – but to date, no such facility has been licensed and operated.[1]

IAEA's Integrated Program for Management of DSRSs

Given the shortage of disposal facilities for DSRSs, an important initiative of the IAEA was to develop an *integrated program* that supports the efforts of Member States to manage and dispose of DSRSs. This program began with the conditioning of radium needles in African countries the early 1990's and the program for Borehole Disposal of DSRSs has grown to encompass the life cycle management of DSRSs; including disposal using the IAEA's Borehole Disposal Concept (BDC), described later. The integrated program includes:

- Collection
- Characterization and inventory control
- Conditioning for storage
- Interim storage
- Analysis of long-term management options
- Analysis of disposal options
- Disposal site selection process
- Design of the BDC
- Development of the safety case for the BDC

[1] In the U.S., DSRSs containing nuclides of nuclear-weapons "defense origin" (e.g., Americium-241) are disposed in the repository for defense transuranic wastes; the Waste Isolation Pilot Plant.

- Licensing a BDC disposal facility
- Disposal (construction / conditioning for disposal / transport / emplacement / closure) and
- Post-closure monitoring. [2]

In addition to the general guidance on the management of DSRSs [2], the IAEA has completed several very useful and specific documents supporting and guiding the management and disposal of DSRSs:

- Disposal Options for Disused Radioactive Sources [10]
- Governmental, Legal and Regulatory Framework for Safety [11]
- Predisposal Management of Radioactive Waste, General Safety Requirements [12]
- Disposal of Radioactive Waste, Specific Safety Requirements [13]
- Borehole Disposal Facilities for Radioactive Waste Specific Safety Guide No. SSG-1 [14]
- The Safety Case and Safety Assessment for the Disposal of Radioactive Waste, Specific Safety Guide [15], and
- Management of Disused Sealed Radioactive Sources [16]

The IAEA's BDC is emphasized in the *IAEA's Technical Manual* [2], because it is the BDC that will allow countries with smaller inventories to develop an in-country disposal facility for DSRSs.

BOREHOLE DISPOSAL CONCEPT FOR DSRSs

Conceptually, the BDC is a multi-barrier disposal system for DSRSs that uses stainless steel capsules and cement barriers to contain and isolate the wastes from the biosphere, with disposal in a borehole at depths greater than 30 m to greatly reduce the likelihood of advertent and inadvertent human intrusion. As well as providing defense in depth, application of the concept provides passive safety in that it does not require human monitoring, maintenance or intervention once the disposal system is sealed. Figure 5 shows a photograph of the two stainless steel engineered barriers. This BDC engineered-barrier system differs from other borehole disposal concepts (see Reference [10] for description of some of the other systems).

Figure 6 shows a schematic of the BDC and Figure 7 shows a close-up of the "near-field" engineered barriers. The technical feasibility and economic viability of the BDC was first assessed in an IAEA-funded Technical Cooperation study completed by the South African Nuclear Energy Corporation (NECSA) in 2000 [17]. The engineered barriers consist of an inner stainless steel "capsule" with a 3-mm wall thickness which holds the DSRSs and is leak-tested after being welded shut. An outer stainless steel "container" with a 6-mm wall thickness holds the capsule. A buffering cement containment barrier fills the space between the capsule and the container. The outer container is 11.5-cm in diameter and the length can be varied.

A single waste package is comprised of: the DSRSs; inside the stainless steel capsule; inside the stainless steel container, with a buffering cement containment barrier between the two containers. Each waste package is cemented in a borehole 26 cm in diameter. Typically, an HDPE casing is used to provide borehole stability during construction and to facilitate waste emplacement operations. The casing serves no safety function, however, the grout filling the annulus between the casing and the borehole wall and the grout backfill within the casing serve to chemically condition groundwaters for a period of time.

Fig. 5. Photograph of BDC Stainless Capsule and Container

Generic Post-Closure Safety Assessments of the BDC

In addition to developing the design, a series of post-closure safety assessments over the past 20 years have investigated the concept's key safety features under varying disposal system conditions. Each of these post-closure safety assessments is generic, using "unit" inventories and generic site settings and climates, and each safety assessment used peak-dose to the public as the metric for measuring safety.

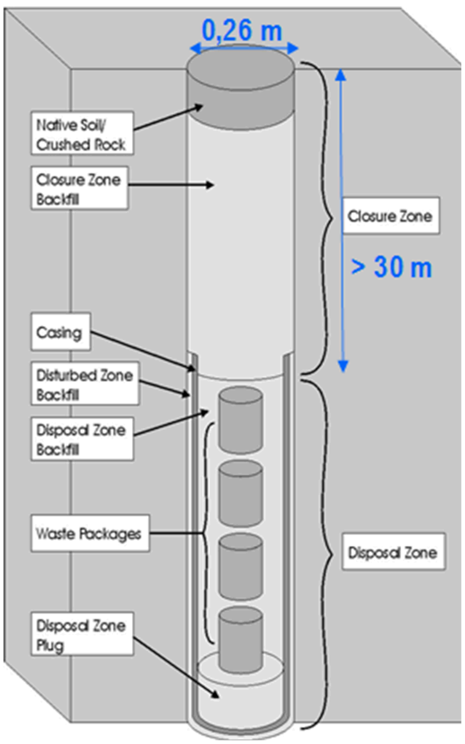

Fig.6. Schematic of the BDC

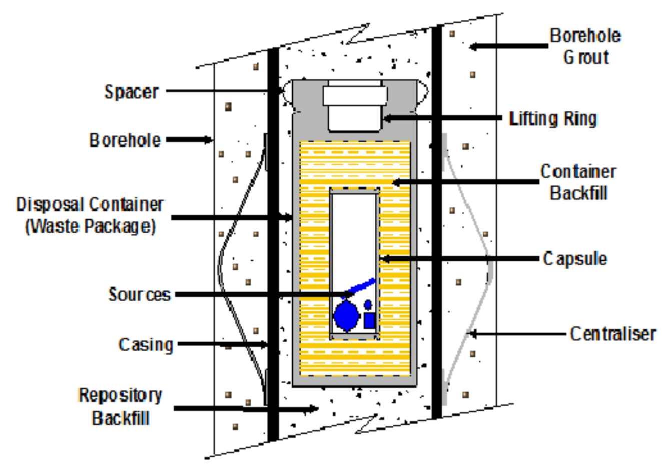

Fig.7. Schematic of the Near-Field of the BDC [18]

The first post-closure safety study focused on disused radium needles, because radium is long-lived (1600-year half-life) and mobile in the environment.[19] Based on these limited, but positive results, a second, generic assessment was undertaken for NECSA for a larger representative inventory of DSRS nuclides. This second assessment also explored performance using a wide range of barriers (stainless steel, copper, lead, cement and bentonite), under a range of geospheres (arenaceous, argillaceous and crystalline), and biospheres (humid, seasonally humid and arid/semi-arid). [20]

A more recent generic safety assessment (GSA) considered an expanded set of 31 radionuclides in unsaturated and saturated conditions. [21] The GSA showed that the containment provided by the waste package would be sufficient for most radionuclides to decay to negligible levels. Only higher levels of long-lived nuclides, such as actinides, under certain disposal conditions, might need to be limited to ensure long-term safety. Most recently, a generic safety assessment has been undertaken specifically to investigate potential impacts from the disposal of high activity DSRS (unpublished). A fundamental conclusion from all these generic post-closure safety assessments is that the BDC concept could be a safe, practical and permanent means of disposing of DSRS for a wide range of nuclides, hydrogeological settings and climatic environments.

Based on the GSA and other studies, locations with certain characteristics should be avoided – including locations with underground natural resources, locations experiencing rapid surficial erosion, locations with a fluctuating water table in the disposal horizon, and locations with aerobic, low pH, high-chloride groundwaters (because such conditions accelerate corrosion of the stainless steel barriers).

The IAEA has also supported the development of two software tools that can be used by Member States in their country-specific safety assessments. [22] The first software tool provides Member States with the capacity to undertake a scoping assessment of potential sites for the BDC based on a site-specific inventory and geochemical characteristics. The scoping tool evaluates cement degradation rates and the containment provided by the engineered barriers under the local groundwater conditions, as known or estimated at the time, in conjunction with a simplified radionuclide transport model involving an abstraction well and the resulting dose to a receptor. The scoping tool does not replace a thorough safety assessment, should a site be selected for further investigation. [23] A second tool, SIMBOD, is an inventory management tool intended to facilitate planning and management during operations and provide a report for post-operational auditing purposes. It also provides a space-filling function to predefine which DSRS can be sealed in which capsules and in which order the disposal packages should be emplaced in a borehole.

Key Elements That Make the BDC Safe

For most nuclides and many geochemical settings, the key elements that make the BDC safe are:

- The BDC is a multi-barrier system, which doesn't rely on any single barrier for safety
- The system is completely passive and does not require human intervention to operate
- The system is viable in either saturated or unsaturated conditions
- Uses materials with well understood properties – including stainless steel and cement
    - The stainless steel will resist corrosion under commonly available geochemical conditions
    - The cement with locally high alkalinity will reduce the corrosion rates of stainless steel, limit radionuclide solubility, form a sorption barrier and limit advective saturated flow
- The small footprint and burial at depths > 30 m greatly limits the likelihood of inadvertent (safety) and adverted (security) human intrusion. The design also incorporates a deflection plate in the borehole above the disposal zone, to deflect a drill bit in the very highly unlikely event of drilling from directly above the borehole.

The BDC is a relatively simple system that does not compromise on safety; and the robust engineered barriers allow deployment in a wide range of geo-hydrologic settings – both saturated and unsaturated.

Costs

The BDC uses economic, readily available materials and technology, including cement, stainless steel and the drilling of a 26 cm-diameter disposal borehole. The scope and cost to implement a BDC program will depend on several country-specific factors such as: the inventory, the siting process, the availability of existing geo-hydrologic information, the availability of drilling equipment, site access, the cost of labor, the regulatory standard, the licensing process, and access to subject matter experts for the Safety Case. The total engineering cost (site characterization, conditioning for disposal and disposal) for a typical inventory is estimated to be several hundred-thousand U.S. dollars (USD); which is less than the cost to repatriate a few high-activity DSRSs. This estimate does not include costs for project management, developing the post-closure and operational safety cases and licensing.

Mobile Hot Cell

A hot cell is required to transfer higher-activity Category 1 and 2 DSRSs from their "source devices" (see Figure 2) to an interim storage container or a stainless steel disposal capsule. Developing countries lack the financial and technical resource to design, construct, qualify and operate a hot cell; and even developed countries may not have an appropriate hot cell – for a one-time set of operations. To address these problems, the IAEA's Waste Technology Section, with additional support from the U.S.

DOE/NNSA, funded NECSA to design, fabricate and test the mobile hot cell, which was first deployed in 2007.

Fitting inside two ISO "sea-land" containers for international shipping, the mobile hot cell consists of a double steel-wall box structure; and the cavity between the walls can be filled with ordinary river sand which reduces the dose rate from a 37 TBq (1000 Ci) Co-60 source to acceptable working levels. [24] Fitted with telescopic master-slave manipulators, a window, and a jib-crane on the inside, this first-ever mobile hot cell has allowed the safe conditioning of DSRS in the Sudan, the Philippines, Brazil and other countries. Figure 8 shows the outside of the mobile hot cell and Figure 9 shows the manipulation of a BDC capsule and container.

Fig. 8. Mobile Hot Cell

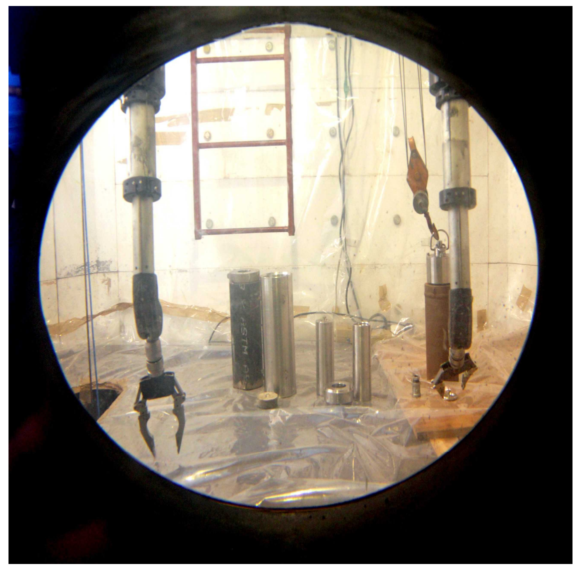

Fig. 9. View of BDC containers and capsules through 1.5 m thick window of mobile hot cell

IMPLEMENTING THE BDC

Canadian Program to Implement the BDC

A key motivation for Canada to take a lead role in addressing the threat posed by unsecure DSRS is to advance Canada's international security commitments made in the context of the Global Partnership, the Nuclear Security Summit process, and the IAEA's Nuclear Security Plans. To date, Canada has invested 1.2 billion dollars (~$934 million USD) to implement these commitments through projects that seek to reduce the threat posed by the proliferation of nuclear, radiological, chemical and biological weapons and related material. To date, Canada has provided the IAEA with ~$42.6 million USD in voluntary contributions for its work.

For Canada, demonstrating the environmental and economic feasibility, as well as the long-term security and sustainability of an operational and licensed BDC, represent an invaluable addition to the range of options for the safe and secure disposal of DSRS. Canada assesses that the implementation of the Malaysian and Ghanan templates in other interested states would greatly assist efforts to reduce international stockpiles of DSRS, which would serve to strengthen national, regional and international security, and allow the continued use of the sources, particularly in developing countries.

The Government of Canada provided a $2.5 million USD grant through its Weapons of Mass Destruction Threat Reduction Program to the IAEA to demonstrate the BDC in Ghana, the Philippines and Malaysia for the safe and secure in-country disposal of DSRSs of all categories. The grant allowed for the respective technical and engineering activities to be undertaken as well addressing the safety case and final licensing of the disposal activities. Allowance was also made for a full-time project manager at the IAEA to manage the implementation and financial aspects related to the project. The goal is to complete the activities by 31 March 2018; a challenging undertaking to complete the first-ever BDC disposal programs in two and one-half years.

Originally scoped for Ghana and the Philippines, it was expanded in 2016 to include Malaysia, as Malaysia was already implementing the BDC, but with their own funding. The IAEA recognized that all three Member States could benefit from the project. Because some decisions still needed to be taken in the Philippines, it was soon apparent that the Philippines could not progress at the same pace. Canada agreed to revise the project to include a scaled down program in the Philippines and to add activities in Malaysia.

Importantly, the modus operandi from the IAEA has been to assist, and not lead, Ghana and Malaysia in implementing the BDC by providing expertise and assistance through specific contracts. This assistance has been provided to both the implementation body in each country and the regulators. The support has been managed to ensure that there is no potential for, nor perception of, a conflict of interest.

Ghana and Malaysia Inventory and Site Setting

The inventory held by the Ghana Atomic Energy Commission (GAEC) consists of 256 DSRSs with a total activity of ~33 TBq (~900 Ci). In contrast, the inventory held by the Malaysian Nuclear Agency (MNA) consists of 12,928 DSRSs with a total activity of ~ 1 TBq (~32 Ci).

The GAEC plans to place their inventory in 13 BDC waste packages with three of the waste packages containing Category 2 sources – which will necessitate the use of the mobile hot cell. The highest activity DSRS is a 22 TBq (604 Ci) Co-60 DSRS. The other DSRSs – Sr-90, Cs-137, Ra-226 and Am-241 – are Category 3 to 5 sources.

In Malaysia, the inventory of 12,928 DSRSs is exclusively Category 3-5 sources (mainly from smoke detectors) that will be contained in ~60 BDC waste packages. The entire inventory can be managed without the use of the mobile hot cell.

Both the GAEC and the MNA propose to place their upper-most waste package far deeper than 30 m; the Ghanaian borehole design foresees disposing of 13 waste packages between 137 m and 150 m below the land surface. The MNA disposal design consists of ~60 waste packages which will be placed 117 m to 177 m below the land surface. These disposal system designs demonstrate that a single borehole can accommodate the entire inventory of DSRSs from two typical countries.

Both the GAEC and the MNA plan to site their disposal facility at their respective research facilities; with the Ghana site being to the north of Accra, and the Malaysian site being 32 km south of Kuala Lumpur. Both sites are tropical.

Site Characterization for the BDC in Ghana and Malaysia

Both programs undertook site-specific geologic drilling and groundwater characterization programs to map the geology, to define the groundwater geochemistry, to refine the BDC facility design and to gather information for the dose-assessment modeling. The IAEA, with Canadian support, supported the program in Ghana, which included (a) a geophysical investigation, (b) the drilling and logging of two rotary percussive boreholes of a depth 150 m each (see Figure 10) and (c) a groundwater characterization program in the boreholes. From this program, it is known that quartzite, phyllite and schist bedrocks are below the top few meters of laterite and clay.

Fig. 10. Drilling One of the Site Characterization Boreholes at the GAEC Site

The water table is a few meters below the surface and the fractures and weak zones in the bedrock produce some groundwater. The IAEA funded a contractor to conduct a pumping test on each borehole and to conduct geochemical characterization of the groundwater in the disposal interval. The highest hydraulic conductivity was measured at 4.49 m/year – but the geochemical parameters of the groundwater in the disposal interval (pH, chloride content and oxidation reduction potential (ORP)) could not be measured due to an equipment failure. Based on water collected from the top of the boreholes, and from other wells, the pH is neutral (~7) and the chloride content is high (~ 770 ppm). Based on the presence of pyrite at depth it is inferred that groundwater conditions in the disposal zone are reducing. To increase confidence in the investigation, a peer review of the site characterization work was conducted by the IAEA and further work is being carried out.

Malaysia self-funded their geologic drilling and groundwater characterization program, which also included a geophysical investigation, the drilling and logging of two cored boreholes and a groundwater characterization program in the boreholes. The site is underlain by schists and phyllites with several breccia and rubble zones present. The pH of the groundwater is mildly acidic at ~5, with a low-chloride content and slightly reducing conditions. The IAEA funded an expert to travel to Malaysia and review the results of the site characterization program (Figure 11).

Fig. 11. Malaysia Site Characterization Report

Disposal Design Work

To assist Ghana and Malaysia, the IAEA is supporting the detailed engineering design of the BDC, and the step-by-step procedures for the disposal operations. The detailed design and procedures for operations that might include disposal of Category 1 and 2 DSRS were cold-tested by NECSA in Pretoria, South Africa. This included use of the MHC and emplacement of DSRS waste packages into a dummy disposal borehole. Many of the reference design elements were adapted, based on the cold test. One of the design and implementation challenges was how to place the cement lid (containment barrier lid) inside the stainless steel container. The initial design called for a precast lid with a lifting eye. However, this initial

Fig. 12. Fresh Grout Filling the Opening of the Containment Barrier

design did not work because the hot cell manipulators could not grab the lid via its lifting eye and some force was needed to push the lid into the opening of the containment barrier; which is difficult in the hot cell.

The design was adapted and the new procedure of pouring cement grout on top of the capsule instead of using a pre-fabricated cement lid was successful (Figure12).

Site-Specific Operational and Post-Closure Safety Cases

The safety case is the document that demonstrates that the disposal operations are feasible and can be conducted safely and that the disposal facility will isolate and contain the radioactive wastes after facility closure. Safety after facility closure is termed "post-closure" safety and potential doses to members of the public are typically used as the measure of safety. The safety case integrates the evidence and arguments that support, justify and quantify safety. For the post-closure safety case, detailed site characterization data, inventory data and BDC design data are used to develop scenarios (based on features, events and processes), to develop mathematical and computer models of the scenarios, and to conduct the performance assessment calculations.

No country has ever prepared a safety case for operational and post-closure safety of a BDC facility for DSRSs. There are generic analyses of the BDC [19, 20, and 21] and there are guidance documents on preparing a safety case [15], and there are example safety cases prepared for mined geologic repositories, but there was no example safety case for the DBC system for Ghana and Malaysia to use as a starting point.

The format for the safety cases began with a recommended format in the GSA [21] and evolved to a more robust format prepared by one of the IAEA peer-reviewers. The software tools implemented in AMBER were used by both programs to assess performance of the engineered barriers and post-closure doses to the public via the groundwater pathway. The initial draft of each safety case was completed in March of 2017. The results of each analysis provided clear evidence that the annual dose standard would be met. Figure 13 provides an example of a graphic depicting the results for "expected performance."

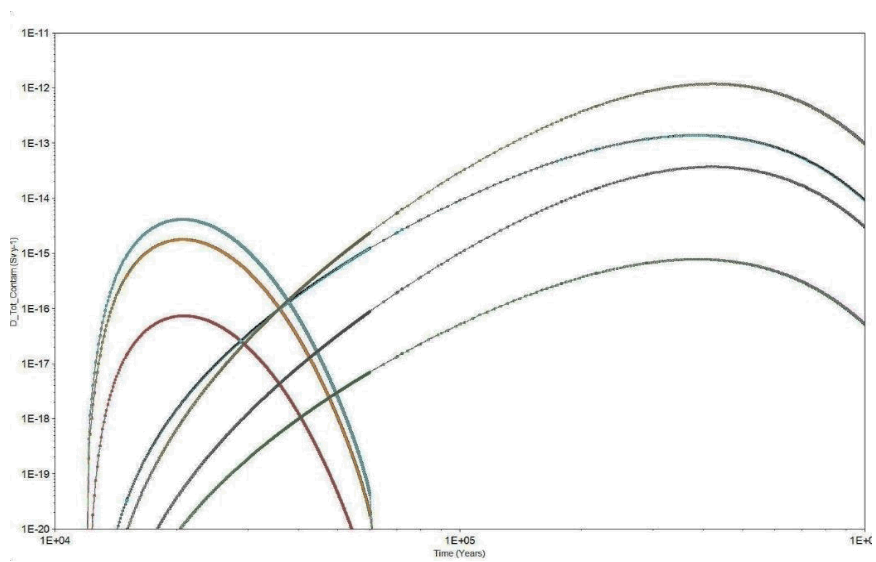

Fig. 13. Annual Dose from each Nuclide, for the expected performance Design Scenario, with Peak Dose being ~ 5.71 x 10^{-10} mSv/yr

The IAEA, with support from Canada, the U.S. Nuclear Regulatory Commission and others sponsored further peer reviews of each safety case in 2017, using a team of international experts hailing from Australia, Germany, South Africa, Sweden, the United Kingdom and the U.S. The IAEA also provided an expert who traveled to Malaysia and Ghana, and assisted each program in updating their safety cases after the peer-review.

Because the geochemistry of the groundwater in the disposal interval in Ghana is not known precisely, two safety cases were prepared, one for reducing groundwater conditions and one for oxidizing conditions. Both assessments showed easy compliance with their 0.3 mSv/year dose standard, however, there are 5 orders of magnitude difference in the peak doses – clearly showing the important influence of the groundwater geochemistry on the performance of the engineered barriers.

An issue the peer reviewers struggled with was the implementation of the IAEA's "graded-approach," where the level of rigor applied to the investigations and implementation should be commensurate with the radiological risk. How high should the bar be set, how rigorous should the peer-review be, when Ghana's inventory is composed almost entirely of short-lived Co-60, with a mere 7 GigaBecquerel (GBq) (0.2 Ci) of Ra-226 and 0.037 GBq (0.001 Ci) of Am-241? Malaysia's inventory is composed almost entirely of the more difficult Am-241, but how high should the bar be set, with a cumulative inventory of 32 Ci, spread across 60 multi-barrier waste packages, at a minimum depth of 117 m? Despite the relatively small inventories (as compared to inventories from nuclear power plants), the peer reviewers recognized these safety cases as being precedence-setting, and held them to a high standard.

Current and Future Status

Today, the two BDC programs are progressing; with Malaysia in the licensing process and Ghana preparing to submit their license application in early 2018. Although the outcome of the licensing processes is yet to be determined; the future looks bright as no fatal flaws have been identified and there is solid momentum in both programs.

SIGNIFICANCE OF WORK

Even with these modest inventories, the results of this work are very significant because:

- The inventory of DSRSs in two countries will likely be safely disposed in-country; permanently eliminating the safety and security liabilities of these sources, and
- These programs are providing a template for other countries to safely dispose of their DSRSs.

CONCLUSIONS

Sealed sources and DSRSs must be safely and securely managed to avoid accidents and security events. Storage is not a sustainable management option for most DSRSs in the long-term. Some short-lived and low activity DSRS may be safely and sustainably disposed of in near-surface disposal facilities (when available), but many others require greater containment and isolation; these may be safety and securely disposed of in boreholes or geological disposal facilities (when available). Canada, the IAEA, the US, and others are assisting the first countries (Ghana and Malaysia) to develop and license borehole disposal solutions for their inventories of DSRSs; setting precedence for other countries to consider borehole disposal as a viable exit-strategy for the management of their own inventories of DSRS.

REFERENCES

1. IAEA, *Code of Conduct on the Safety and Security of Radioactive Sources*, International Atomic Energy Agency, Vienna (2004).
2. IAEA, *BOSS: Borehole Disposal of Disused Sealed Sources: A Technical Manual,* IAEA-TECDOC-1644, International Atomic Energy Agency, Vienna (2011).
3. National Council on Radiation Protection and Measurements, *Management of Terrorists Events Involving Radioactive Material,* NCRP Report No. 138, (2001).
4. U.S. General Accounting Office, Nuclear Nonproliferation – *U.S. and International Assistance Efforts to Control Sealed Radioactive Sources Need Strengthening,* GAO-03-638, Washington DC, https://www.gpo.gov/fdsys/pkg/GAOREPORTS-GAO-03-638 (2003).
5. James Martin Center for Nonproliferation Studies, *CNS Global Incidents and Trafficking Database, Tracking, publicly reported incidents involving nuclear and other radioactive materials, 2016 Annual*, http://www.nti.org/media/documents/global_incidents_and_trafficking_2016.pdf, (2017).
6. J.R. Cochran and L Price, *Nuclear News*, "How Sand and Science Can Solve a Ubiquitous International Security Threat," (August 2006).
7. IAEA, *Guidance on the Import and Export of Radioactive Sources,* International Atomic Energy Agency, Vienna (2012).
8. (25% are now DSRS NEED CITATION).
9. U.S. Nuclear Regulatory Commission, *Branch Technical Position on Waste Averaging and Encapsulation Vol 1*, Table 2 (2015).
10. IAEA, *Disposal Options for Disused Radioactive Sources,* IAEA-Technical Report 436, International Atomic Energy Agency, Vienna (2005).
11. IAEA, *Governmental, Legal and Regulatory Framework for Safety,* IAEA-GSR Part 1 (Rev. 1). International Atomic Energy Agency, Vienna (2016).
12. IAEA, *Predisposal Management of Radioactive Waste General Safety Requirements,* IAEA-GSR Part 6. International Atomic Energy Agency, Vienna (2009).
13. IAEA, *Disposal of Radioactive Waste Specific Safety Requirements,* IAEA-SSR-5. International Atomic Energy Agency, Vienna (2011).
14. IAEA, *Borehole Disposal Facilities for Radioactive Waste Specific Safety Guide,* IAEA-SSG-1. International Atomic Energy Agency, Vienna (2009).
15. IAEA, *The Safety Case and Safety Assessment for the Disposal of Radioactive Waste, Specific Safety Guide,* IAEA-SSG-23, International Atomic Energy Agency, Vienna (2012).
16. IAEA, *Management of Disused Sealed Radioactive Sources,* IAEA NW-T-1.3 International Atomic Energy Agency, Vienna (2014).
17. J.J. van Blerk, J.J.P., Vivier, M.A.G. Andreoli, and R.G. Heard, *The Borehole Disposal Concept for Spent Sources – Volume I: Development and Evaluation of the Concept,* Atomic Energy Corporation of South Africa, Internal Report No. GEA-1353, Pretoria (2000).
18. R.G. Heard, *Background Information Document on the Project to Investigate a Borehole as a Disposal Option for Disused Sealed Radioactive Sources (DSRS)*, South African Nuclear Energy Corporation, GEA-1618, Pretoria (2004)
19. M.W. KOZAK, et al., *Borehole Disposal of Spent Sources, Volume II: Preliminary Safety Assessment of the Disposal Concept*, NECSA Report GEA-1353, Pretoria (2000)]
20. R.H. LITTLE, et al., *Generic Post-Closure Safety Assessment and Derivation of Activity Limits for the Borehole Disposal Concept,* Quintessa Report QRS-1128A-6 v1.0, Henley-on-Thames (2003).
21. IAEA, *Generic Post-Closure Safety Assessment for Disposal of Disused Sealed Sources in Narrow Diameter Boreholes*. IAEA-TECDOC-1824. International Atomic Energy Agency, Vienna (2017).
22. P.C. ROBINSON, et al., *The Borehole Disposal Concept Scoping Tool v2.0: User Guide,* Quintessa Report QRS-3038B-2 v1.0, Henley-on-Thames (2016).
23. R.H. Little, Post-Closure Safety of the Borehole Disposal Concept, *IAEA Conference on the Safety of Radioactive Waste Management*, Vienna (2016).

24. G.R. Liebenberg and M. Al-Mughrabi, "The Development of a Mobile Hot Cell Facility for the Conditioning of Spent High Activity Radioactive Sources (SHARS) – 8436", *Proceedings from the WM2008 Conference*, Phoenix, Arizona (2008).

ACKNOWLEDGMENTS

Though this paper highlights the external support, it is the GAEC and the MNA that deserve the lion's-share of the credit, as they have been responsible for carrying-out their disposal programs. Additionally, many consultants and contractors, too numerous to individually mention, have been involved in developing the concept to its current status as an implementable option for the disposal of DSRSs.