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Disposal Options for Disused Radioactive Sources

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DISPOSAL OPTIONS FOR
DISUSED RADIOACTIVE SOURCES

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DISPOSAL OPTIONS FOR DISUSED RADIOACTIVE SOURCES

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FOREWORD

Sealed radioactive sources are used worldwide in medicine, industry and research for a wide range of applications. The sources can contain a broad spectrum of radionuclides, exhibiting a wide range of activity levels and radioactive half-lives. At the end of their useful lives, usually 5–15 years, sources are defined as 'spent' or 'disused'. However, the residual level of radioactivity in some sources can remain high, representing a significant radiological hazard. There have been several cases in which mismanagement of radioactive sources has resulted in serious radiological accidents in some Member States, for example Brazil, Estonia, Georgia, the Islamic Republic of Iran, Peru and Thailand. Disused radioactive sources must be considered as a specific type of radioactive waste that needs to be managed safely. Its safe disposal ensures the elimination of the security threat posed by radioactive sources during storage. Without appropriate disposal facilities, the safe and secure long term management of the source inventory cannot be guaranteed.

Recently, concern has arisen that improperly managed radioactive sources could potentially be used in radiological dispersion devices (so-called dirty bombs) for acts of terrorism. Regardless of the level of development of their nuclear activities, almost all countries have existing inventories of disused radioactive sources in storage. This practice is not considered sustainable in the long run and in many cases may represent a high risk situation with regard to both the health hazard and the security threat posed by high activity long lived sealed sources.

To address these concerns and to provide guidance to Member States on the safe management and disposal of disused radioactive sources, the IAEA has taken several steps to lower the risks associated with radioactive sources and the likelihood of potential incidents and accidents. These include: (a) establishment of the Code of Conduct on the Safety and Security of Radioactive Sources; (b) adoption of a binding international regime on the safety of radioactive waste management and spent fuel, including sealed sources; and (c) formulation of a revised action plan for the safety and security of radioactive sources. These serve as international instruments by which the IAEA's activities relating to the safety and security of radioactive sources can be strengthened and implemented. To further highlight the issue, an international conference on the Security of Radioactive Sources was organized and hosted by the IAEA in March 2003. The conference advocated the promotion of greater international cooperation in addressing the security concerns raised by insufficiently controlled radioactive sources.

Disused radioactive sources exhibit a high degree of variability in their physical and radiological properties (half-lives, specific and total activities, physical size, etc.). This means that a wide spectrum of options may be available for their disposal, ranging from near surface and mined cavern disposal facilities to geological repositories, including borehole type facilities of varying designs and depths.

This report reviews relevant information on technical factors and issues, as well as approaches and technologies leading to the identification of potential disposal options for disused radioactive sources. It attempts to provide a logical ‘road map’ for the disposal of disused radioactive sources, taking into consideration the high degree of variability in the radiological properties of such types of radioactive waste. The use of borehole or shaft type repositories is highlighted as a potential disposal option, particularly for those countries that have limited resources and are looking for a simple, safe and cost effective solution for the disposal of their radioactive source inventories. With this in mind, the IAEA is also preparing a safety guide on borehole disposal of disused radioactive sources.

It is anticipated that this report will be of relevance to both policy makers and repository developers in Member States that are exploring options or developing strategies for the safe and secure disposal of disused radioactive sources. It is intended to respond to the disposal needs of the various Member States, ranging from countries that have existing repositories or are planning to develop new disposal facilities to countries that have no need to develop conventional disposal facilities but will require a dedicated facility for the disposal of disused radioactive sources.

This report was developed with the help of consultants and through a Technical Committee Meeting held in Vienna in May 2003. The IAEA wishes to express its thanks to all the participants who were involved in the preparation of this report and in particular to N. Chapman for his assistance in finalizing it. The IAEA officer responsible for the report was R. Dayal of the Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

1.1. BACKGROUND

Sealed radioactive sources have been used globally for many decades in a wide range of applications in medicine, industry and research. At the end of their useful life, usually 5–15 years, the radioactive sources are defined as 'spent' or 'disused'. However, the residual level of radioactivity in some sources can still be high, representing a significant radiological hazard. Many sources are small shiny metallic objects, potentially attractive to the inquisitive who do not know what they are. If not properly managed and disposed of, such disused radioactive sources pose a potential health hazard to the public for periods, depending on the half-life and activity level of the radionuclides, which may extend to hundreds or thousands of years. They can also present immediate security concerns. If they are not strictly controlled the sources might be stolen and their radioactive materials used in radiological dispersion devices ('dirty bombs') for acts of terrorism.

The high activity and concentration of residual radioactivity of some disused sources, combined with the long half-lives of some of the radionuclides used in them, can pose problems in conventional national waste management schemes. In many countries there are types of radioactive sources that do not fall into the category of wastes normally acceptable for disposal in national near surface repositories. This is because the anticipated institutional control period may not be sufficiently long to allow the sources to decay to safe levels. The alternative option of geological disposal is not yet available and, in many Member States, may never become available. As a result, disused radioactive sources are currently kept in storage in almost all countries — a practice that is not considered sustainable in the long run and which, in many cases, may represent a high risk situation [1]. Without appropriate disposal facilities, the safe and secure long term management of the sources cannot be fully guaranteed.

Large inventories of disused radioactive sources exist in many countries that have no other nuclear activities and therefore represent the only radioactive waste that needs to be managed safely. The absence of nuclear activities may also contribute to the risk associated with the management of disused radioactive sources since these countries often lack the necessary infrastructure and technical personnel required for the safe management of radioactive waste.

During the past decade, the IAEA and its Member States have taken steps to lower the risks associated with disused radioactive sources and the likelihood of incidents and accidents, including the establishment of the Code of Conduct on the Safety and Security of Radioactive Sources [2]. Various activities are being implemented to improve the management of disused radioactive sources in order to ensure that they are manufactured, handled, used, transported, stored and recycled or disposed of in a technically sound, cost effective and safe manner [3–6]. Simultaneously, a binding international regime for the safety of radioactive waste management and spent fuel (the Joint Safety Convention) has been adopted [7]. In addition, IAEA Safety Standards [8, 9] and ICRP recommendations related to disposal [10] have been developed and improved upon as more experience in radioactive waste management is gained.

Although significant progress has been made in the management of low, intermediate and high level wastes, the long term safety and security of disused radioactive sources continues to be a subject of concern at the international level [11–13]. This was again highlighted at an international conference on the Security of Radioactive Sources hosted by the IAEA in March 2003 [14]. The conference advocated the promotion of greater international cooperation in addressing the security concerns raised by insufficiently controlled radioactive sources.

Subsequently the IAEA Secretariat developed an updated action plan for the safety and security of radioactive sources, which provides an international instrument whereby the IAEA's activities relating to the safety and security of radioactive sources can be strengthened and implemented. An important component of the plan is the promotion of research and development related to the disposal of radioactive sources. The plan also gives consideration to the development of regional or multinational facilities for the disposal of disused radioactive sources, which is particularly attractive for developing Member States since many of these countries do not have the technology or the resources to implement a national disposal facility of their own. Furthermore, the small inventories of radioactive sources in many of these countries provide a sound rationale for sharing the development of a regional repository.

Disused radioactive sources exhibit a high degree of variability in their physical and radiological properties (half-lives, specific and total activities, physical size, etc.). This means that a wide spectrum of options may be applicable to their disposal, ranging from near surface and mined cavern disposal facilities to geological repositories, including borehole type facilities of varying depths. The most appropriate solution for a Member State will depend on many factors, including the availability of nuclear expertise and relevant infrastructure in the country, national waste management policies, the regulatory framework, financial resources, etc.

Some disposal options are only likely to be applicable to Member States that have active nuclear programmes and existing or planned conventional near surface or geological repositories for the disposal of their waste inventories. A particular issue of concern is the disposal of disused radioactive sources in Member States that have no other radioactive waste and, as a result, have no need to develop conventional disposal facilities. It is in these Member States with limited infrastructure and resources that there is an urgent need for a safe, technically sound and cost effective disposal option for disused radioactive sources. Again, the small inventories of radioactive sources in many of these countries provide a sound rationale for sharing the development of a regional repository.

Keeping these issues in mind, this report highlights the use of borehole or shaft type repositories for the disposal of disused radioactive sources. This option is particularly attractive for developing Member States in that it has a number of potentially favourable technological and safety features. Apart from the much lower cost, it is relatively easy to implement, allows modular application and a great deal of flexibility in design, has no large initial investment and infrastructure requirements, and is less intrusive on the landscape than a mined repository. Because of the unique design features, in particular the design and depth flexibility and small footprint, a borehole type repository has the potential to dispose of, safely and securely, the entire source inventory in a Member State. The difficulty of retrieving waste from a borehole facility would also contribute significantly to permanently eliminating the security threat posed by high activity long lived disused radioactive sources.

1.2. OBJECTIVE

The main objective of this report is to discuss disposal options for disused radioactive sources, ranging from conventional near surface and rock cavity facilities to geological repositories, including emplacement in shafts and boreholes drilled from the surface. The purpose of the discussion is to identify suitable disposal strategies for the different types of disused radioactive sources and to illustrate a rational approach that would allow sensible decisions to be made concerning their disposal.

It is anticipated that this report will be useful and of direct relevance to both policy makers and repository developers in Member States that are exploring options or developing strategies for the safe and secure disposal of disused radioactive sources. The report is intended to respond to the disposal needs of various Member States, ranging from countries that have existing repositories or are planning to develop new disposal facilities, to countries that have no need to develop conventional disposal facilities but will require a dedicated facility for the disposal of disused radioactive sources.

1.3. SCOPE

This report reviews relevant information on technical factors and issues, as well as approaches and relevant technologies, leading to the identification of potential disposal options for disused radioactive sources. It attempts to provide a logical 'road map' for the disposal of disused radioactive sources, taking into consideration the high degree of variability in the radiological properties of such types of radioactive waste.

The use of borehole or shaft type repositories is highlighted as a potential disposal option, particularly for those countries that have limited resources and are looking for a simple, safe and cost effective solution for the disposal of their radioactive source inventories.

The information provided in this report can be adapted or adopted to identify and develop specific disposal options suitable for the type and inventory of radioactive sources kept in storage in a given Member State. The material contained here has been extracted from other IAEA publications, as well as relevant published materials from Member States and other international organizations.

1.4. STRUCTURE

Section 2 describes the uses and characteristics of radioactive sources. Section 3 provides information on the range of disposal options that may be applicable to the management of radioactive sources. Section 4 describes a process for screening these disposal options and identifying the one (or more) that is most appropriate. Section 5 outlines the considerations affecting packaging and conditioning of radioactive sources for disposal once an option is selected, and discusses the implications of waste acceptance criteria for different options. Section 6 contains the conclusions of the report, and the annex provides more information on the borehole disposal option, which emerges as particularly suitable for Member States with small inventories and/or no other significant amounts of radioactive waste to manage.

2. USES AND CHARACTERISTICS OF RADIOACTIVE SOURCES

Sealed radioactive sources are widely available and are used extensively in a broad range of applications. They are generally small (typically a few centimetres in size) and the radionuclides are generally enclosed in capsules made, with very few exceptions, of stainless steel, titanium, platinum or other inert metals. Source capsules are airtight and durable. The radionuclides may also be closely bonded to a substratum. The recommended useful life of most sealed sources is 5–15 years, but they represent a potential radiation hazard long after the devices containing them have been decommissioned.

According to the Basic Safety Standards (BSS) [9], the capsule or material of a sealed source should be strong enough to maintain leaktightness under the conditions of use and wear for which the source was designed, and should also be able to withstand foreseeable mishaps. Older sources do not necessarily provide the same level of integrity.

The source may be marked with an engraved serial number and, for sources with sufficiently large dimensions, the radionuclide activity and date of manufacture may be given. Higher activity sources are usually contained in a double walled capsule made of a corrosion resistant metal such as stainless steel [3].

In most cases the source capsule will be undamaged at the time it is collected for long term storage or disposal. However, its integrity either before or after conditioning cannot be taken for granted, nor can the longevity of the source capsule be guaranteed after disposal.

2.1. USES OF RADIOACTIVE SOURCES

Radioactive sources may contain one of dozens of radionuclides, and their activities can range from ~10^5 to 10^{17} Bq. Most sources have activities of less than 5 GBq. The half-lives of the typical isotopes can range from 70 d for ^{192}Ir to 1600 a for ^{226}Ra. Less commonly used isotopes such as ^{14}C and ^{129}I have half-lives in the range of thousands to millions of years. However, such very long lived radionuclides are used only in calibration sources that contain small amounts of radioactivity.

2.1.1. Medical applications

Hospitals and medical facilities are among the largest users of radioactive sources, typically for teletherapy and brachytherapy applications. Until the

1950s, the only significant radioactive sources produced were the ^{226}Ra sources that were used for brachytherapy. Most of the old radium sources used in brachytherapy have been replaced by ^{60}Co, ^{137}Cs and ^{192}Ir. Cobalt-60 is the most common radionuclide used in teletherapy, although some ^{137}Cs sources are also in use. Gamma radiation is used to treat approximately half of all cancer patients with solid tumours. Cobalt and caesium teletherapy sources are among the higher activity sources in general use.

2.1.2. Applications in research and education

Radioactive sources used in education and research contain a wide variety of radionuclides. A radioactive source is often purchased for a specific project and then set aside after completion of the project. During the 1960s, gamma irradiators containing large quantities of ^{60}Co were used for research purposes. Soil moisture gauges used for agricultural research contain ^{137}Cs sources and neutron producing ^{241}Am–Be sources.

2.1.3. Industrial applications

Iridium-192 is typically used for industrial radiography, such as the non-destructive imaging of pipe welds. Cobalt-60 and ^{137}Cs sources are also used for industrial radiography. Large neutron and gamma sources are used in mining, as well as in oil and gas well logging. These neutron sources contain either ^{238}Pu–Be or ^{241}Am–Be. Californium-252 and a few ^{226}Ra–Be neutron sources are also in use. The activity of some ^{241}Am neutron sources used in well logging can be as high as several hundreds of GBq per source but are usually within the range of 1–800 GBq.

The most common industrial radioactive sources are used in level and thickness gauges and in process control. If these gauges are not removed when a facility is closed, they can end up in metal recycling facilities.

Radioisotope thermoelectric generators (RTGs) use heat generated by decay of radioactive isotopes to produce electric power. They have no moving parts and can operate for decades without refuelling. They are used as a power supply where frequent maintenance or refuelling is expensive or impractical. Most terrestrial RTGs are fuelled with ^{90}Sr. The largest known RTG was fuelled with 25 PBq of ^{90}Sr. An RTG typically contains about 2 PBq of ^{90}Sr.

Industrial irradiators containing ^{60}Co or ^{137}Cs as radioactive sources are used to sterilize medical products, meat, fresh vegetables and other foodstuffs. Although physically small (approximately 1 cm × 50 cm), the radioactive sources or ‘pencils’ in irradiators are highly radioactive. Individual cobalt pencils can have an activity of 500 TBq and an irradiator facility may have an array of cobalt pencils totalling up to a few hundred PBq. The highest activity caesium irradiators may contain as much as 8 PBq of ^{137}Cs.

2.2. INVENTORY OF RADIOACTIVE SOURCES

The current inventory of sealed radioactive sources worldwide is likely to be in the millions, although the existing registries indicate a smaller number. The total number of sources sold in the European Union alone during the past 50 years is estimated to be higher than 500 000. For various reasons, a significant number of radioactive sources have become obsolete or surplus. These surplus, obsolete and unwanted radioactive sources are termed disused. Out of the millions of radioactive sources known to have been produced worldwide, the IAEA estimates that approximately 20% are categorized as disused. If improperly managed, these sources can cause serious injuries, deaths and radioactive contamination of the environment.

2.3. PROPERTIES OF DISUSED RADIOACTIVE SOURCES

Data on radionuclides and activities in sealed radioactive sources have recently been reviewed by the IAEA [15]. The data provide minimum, maximum and typical radioactivity levels in the sources. Table 1 provides a summary of the main applications and half-lives of radionuclides used in sealed radioactive sources. Table 2 shows the most common radionuclides used in radioactive sources and the minimum and maximum level of radioactivity for each radionuclide. It can be seen that the maximum activities are for the individual sources within industrial irradiators and for RTG sources, and that the maximum activities for the main types of sources span a range of 10^8 Bq. The strongest sources, by some orders of magnitude, are ^{60}Co, ^{90}Sr and ^{137}Cs.

Radioactive sources with half-lives of less than about 100 days will decay to safe levels in a few years. From a waste management point of view such sources can be safely allowed to decay in storage or in near surface disposal facilities. This does not mean that short half-life radioactive sources are without hazard. For example, mismanagement of a 185 GBq ^{192}Ir radioactive source led to a serious radiological accident in the Islamic Republic of Iran in 1996 [16]. Similar accidents have occurred in Brazil, Estonia, Georgia and Thailand [17–20].

The radionuclides in the strongest source category (^{60}Co, ^{90}Sr and ^{137}Cs) are those with moderate half-lives between about 5 and 30 years. With such high strengths and moderate half-lives these sources require isolation for hundreds to thousands of years.

TABLE 1. MAIN APPLICATIONS OF SEALED RADIOACTIVE SOURCES, RADIOISOTOPES USED AND THEIR HALF-LIVES [14]

Application	Main radionuclide	Half-life
RTGs	^{90}Sr	28.6 a
	^{238}Pu	87.8 a
Irradiators	^{60}Co	5.3 a
	^{137}Cs	30.1 a
Teletherapy	^{60}Co	5.3 a
	^{137}Cs	30.1 a
Industrial radiography	^{60}Co	5.3 a
	^{192}Ir	74 d
	^{75}Se	120 d
	^{169}Yb	32 d
	^{170}Tm	129 d
Brachytherapy	^{60}Co	5.3 a
	^{137}Cs	30.1 a
	^{226}Ra	1600 a
	^{192}Ir	74 d
	^{125}I	60 d
Industrial gauges	^{60}Co	5.3 a
	^{137}Cs	30.1 a
	^{252}Cf	2.6 a
	^{85}Kr	10.7 a
	^{241}Am	432 a
	^{244}Cm	18.1 a
Research	^{241}Am–Be	432 a
	^{239}Pu–Be	24 100 a
	^{241}Am–Be	432 a
Well logging/moisture gauges	^{137}Cs	30.1 a
	^{252}Cf	2.6 a
Pacemakers	^{238}Pu	87.8 a

The actinide inventory of radioactive sources consists primarily of radionuclides such as plutonium and americium used in ^{238}Pu–Be and ^{241}Am–Be neutron sealed sources, ^{241}Am gamma sources and ^{238}Pu heat sources. Many old

TABLE 2. COMMONLY USED RADIOISOTOPES IN SEALED RADIOACTIVE SOURCES (HALF-LIFE > 0.1 a)

Radionuclide	Exemption level[a] (Bq)	Minimum for nuclide[b] (Bq)	Maximum for nuclide[c] (Bq)
^{125}I	1.00E + 06	1.5E + 09	3.0E + 10
^{192}Ir	1.00E + 04	7.4E + 08	7.4E + 12
^{75}Se	1.00E + 06	3.0E + 12	3.0E + 12
^{170}Tm	1.00E + 06	7.4E + 11	7.4E + 12
^{210}Po	1.00E + 04	1.1E + 09	4.1E + 09
^{153}Gd	1.00E + 07	7.4E + 08	5.6E + 10
^{57}Co	1.00E + 06	5.6E + 08	1.5E + 09
$^{106}Ru/^{106}Rh$	1.00E + 05	8.1E + 06	2.2E + 07
^{109}Cd	1.00E + 06	7.4E + 08	5.6E + 09
^{147}Pm	1.00E + 07	1.9E + 09	1.9E + 09
^{252}Cf	1.00E + 04	1.1E + 06	4.1E + 09
^{55}Fe	1.00E + 06	1.1E + 08	5.0E + 09
^{60}Co	1.00E + 05	9.3E + 09	5.6E + 17
^{85}Kr	1.00E + 04	1.9E + 09	3.7E + 10
^{3}H	1.00E + 09	1.9E + 09	1.1E + 12
^{244}Cm	1.00E + 04	7.4E + 09	3.7E + 10
^{90}Sr	1.00E + 04	3.7E + 08	2.5E + 16
^{137}Cs	1.00E + 04	3.0E + 08	1.9E + 17
^{238}Pu	1.00E + 04	1.1E + 11	1.0E + 13
^{63}Ni	1.00E + 08	1.9E + 08	7.4E + 08
^{241}Am	1.00E + 04	4.8E + 07	8.5E + 11
^{226}Ra	1.00E + 04	2.6E + 05	1.9E + 09
^{239}Pu–Be	1.00E + 04	7.4E + 10	3.7E + 11

[a] Exemption levels from Ref. [9].
[b] Minimum in individual sealed radioactive sources [15].
[c] Maximum in individual sealed radioactive sources [15].

radioactive sources used in medical treatment contain ^{226}Ra (e.g. radium needles). With half-lives ranging from 87 a for ^{238}Pu to 1600 a for ^{226}Ra, this group of radioactive sources may pose a potential health hazard for thousands of years.

Sources used for the calibration of instruments may contain extremely long lived radionuclides such as ^{14}C (half-life = 5700 a), ^{36}Cl (half-life = 300 000 a) and ^{129}I (half-life = 17 million a), but their activity is generally low and of negligible radiological significance.

The ranges of activities for the different radionuclides in sealed radioactive sources are plotted in Fig. 1 as a function of half-life of the sources, together with the exemption levels for the radionuclides from Ref. [9]. The wide range of source strengths for ^{60}Co, ^{90}Sr and ^{137}Cs radionuclides is apparent, as is their dominance in terms of maximum strengths. In storage or in a disposal facility, the radioactivity in these sources will decay. Figures 2–4 show the effects of 100, 300 and 1000 years of decay, respectively. Both 100 and 300 years are periods commonly considered for institutional control of near surface repositories. After 100 years all sources with a half-life of less than 5 years have decayed to less than the exemption level (Fig. 2). In this context exemption levels are a useful tool to judge when a source will have decayed to a safe level, although actual safety can be determined only by analysing exposure scenarios for the facility where the source might be disposed of. For many types of disposal facilities, such analyses might indicate that the risk presented by sources meets regulatory requirements even before they have decayed to exemption levels, so the decay to exemption approach presented here is a conservative way of considering the radiological hazard from sources.

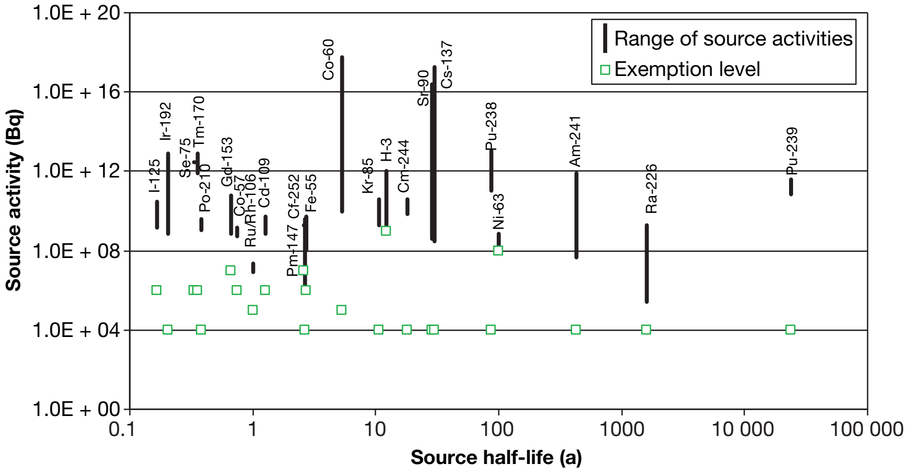

FIG. 1. Ranges of source activities for various radionuclides.

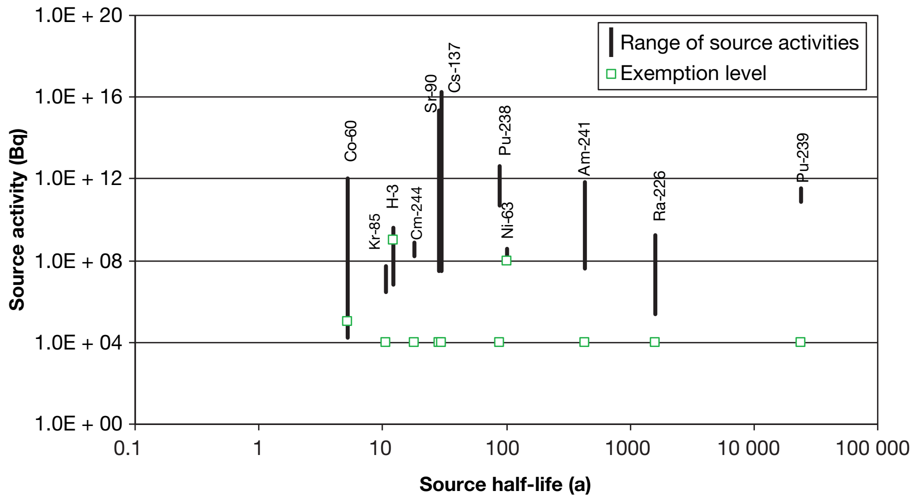

FIG. 2. The effect of 100 years of decay on the ranges of source activities.

After 300 years, ^{60}Co (half-life = 5.3 a), a very important radionuclide in a large number of sources, has decayed to harmless levels along with ^{85}Kr and ^{3}H (Fig. 3). However, it can also be seen that none of the ^{90}Sr or ^{137}Cs sources in the survey decays to the exemption levels in 300 years and they will thus

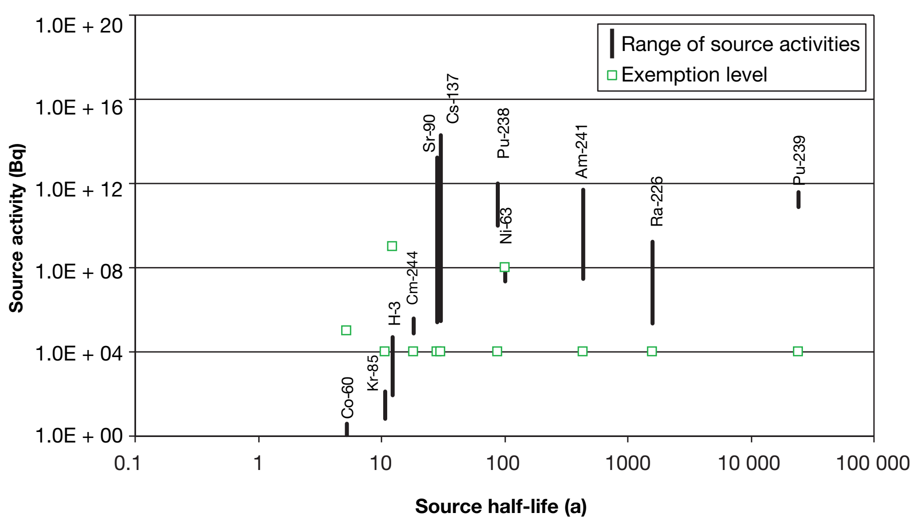

FIG. 3. The effect of 300 years of decay on the ranges of source activities.

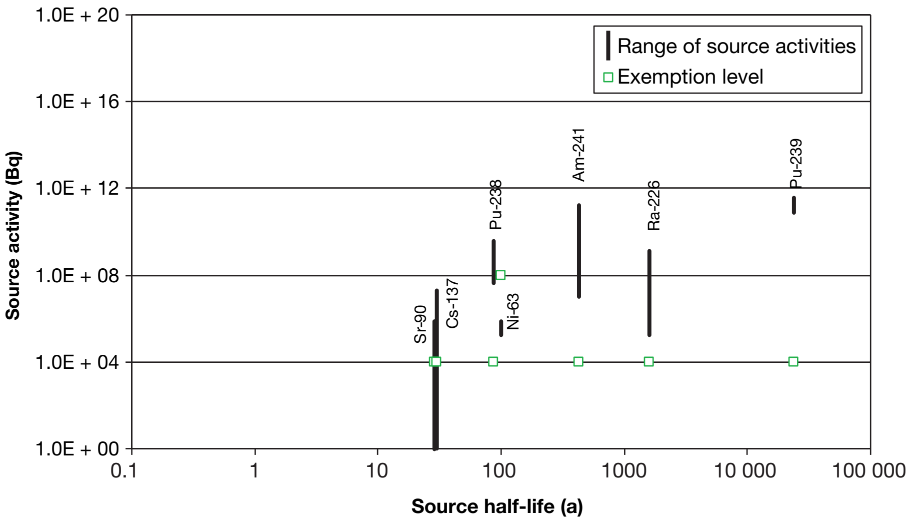

FIG. 4. The effect of 1000 years of decay on the ranges of source activities.

continue to represent point sources of elevated activity if they are disposed of in a near surface repository, even after the conventional institutional control period. Figure 4 shows that beyond 300 years, for high strength sources there is little to be gained by any additional institutional control period that might be considered reasonable. Even after 1000 years of decay, the high strength ^{90}Sr and ^{137}Cs sources are still some orders of magnitude above the exemption level and none of the longer lived radionuclides has significantly decayed. It is important to note that these observations are general in nature and that in practice the actual acceptance of sources in a disposal facility needs to be authorized by the national regulatory body on the basis of a specific safety assessment. This is discussed further in Section 4.

2.4. CHARACTERISTICS OF THE MAIN RADIOISOTOPES IN SEALED SOURCES

The physical and chemical properties of the radioactive substances contained in radioactive sources differ considerably [1]:

(a) Americium has chemical characteristics similar to the rare earth metals. Americium oxides are normally used in sources as americium metal is not stable. For neutron sources, fine americium oxide powder is mixed with beryllium powder. Alpha particles emitted by the americium interact with the beryllium to produce neutrons. Most neutron sources contain Am–Be in powder or pellet form, but some contain the Am–Be in sintered form. When americium is used as a low energy gamma source, the stainless steel capsule has a thin screen at one end to allow the low energy gamma radiation to be emitted without attenuation.

(b) Caesium is an alkaline metal similar to potassium and sodium. Caesium is very reactive and can only be used as a salt. Caesium chloride is often used, but some ^{137}Cs sources are prepared in ceramic form, making the radionuclide virtually insoluble in water. However, this technique is only suitable for weak sources because it results in reduced specific activity.

(c) Cobalt in sealed radioactive sources is in the metallic form since this gives the highest specific activity. Usually the cobalt is in the form of thin discs or small cylindrical pellets. Metallic cobalt is stable in air, but a thin layer of oxide forms on its surface which may cause contamination if unprotected cobalt is handled. For this reason the cobalt used in radioactive sources is nickel plated before activation. Cobalt as a metal is not soluble in water.

(d) Iridium is a noble metal which is not oxidized in air or dissolved in water. These are excellent characteristics for a radioactive source material.

(e) Plutonium sources are used in RTGs, in neutron generators and for calibration. The neutron sources consist of plutonium combined with beryllium, which are fused in a ceramic configuration for stability.

(f) Radium is a very reactive alkaline earth metal used in the form of salts, such as bromides, chlorides, sulphates or carbonates. All are soluble and can give rise to radiological problems if released. These salts may easily be dispersed as powder if the source encapsulation is damaged.

(g) Strontium sources can have an oxide or titanate form. For medical applications the strontium compound is contained in a silver plate and screened with 0.1 mm palladium coated silver. For other applications the strontium compound may be incorporated in a ceramic or glass bead, or rolled silver foil.

(h) Tritium sources are often used for radioluminescent devices which contain tritium gas and phosphor. The brightness and size of a radioluminescent device determine how much tritium activity the device contains when manufactured.

3. DISPOSAL CONSIDERATIONS

3.1. GENERAL

The IAEA classification of radioactive waste [21] provides a generic approach to radioactive waste management. Radioactive waste is categorized as exempt waste, short lived low and intermediate level waste, long lived low and intermediate level waste, and high level waste. Potential disposal options have been identified for each waste category, based on its specific characteristics, with the concentration of activity and longevity of the radioactive waste components being the key distinguishing features, as shown in Table 3.

Near surface repositories, where the disposal units are within tens of metres of the surface, provide adequate containment for short lived low and intermediate level waste and for some long lived low and intermediate level waste when greater confinement is provided. Institutional controls provide assurance of adequate performance of the waste isolation barriers during the period of their anticipated duration. The rationale of near surface disposal depends on the assumption that, by the end of the institutional control period, the activity of the waste will have decayed to harmless levels with respect to likely future uses of the site and consequent potential exposure pathways, as shown by safety assessments. The duration of institutional controls is an important strategic decision with implications for various aspects of the development of the disposal system, including definition of waste acceptance criteria.

Geological disposal is required for some long lived low and intermediate level waste and for high level waste. The depth required for geological disposal depends on the geological environment of a specific site and the amount and type of waste to be disposed of.

The IAEA has developed generic safety requirements for the near surface disposal of radioactive waste [21] and guidance on the safety assessment of this option [22]. Issues related to safety standards on the geological disposal of radioactive waste are addressed in Refs [8, 23]. These requirements, as well as relevant technical criteria and socioeconomic and other non-technical considerations [22–29], are also applicable to the disposal of disused radioactive sources.

TABLE 3. CLASSES OF RADIOACTIVE WASTE AND POTENTIAL DISPOSAL OPTIONS [16]

Waste class	Properties	Disposal options
Exempt waste	Activity below clearance levels Based on annual dose to members of critical groups of less than 10 μSv	No restrictions
Low and intermediate level waste	Activity higher than class 1 Negligible thermal power	
Short lived	Content of long lived radionuclides restricted by the regulatory authority on the basis of safety considerations	Near surface or geological disposal
Long lived	Content of long lived radionuclides above limits for short lived waste	Geological disposal (near surface disposal in greater confinement disposal facilities may be possible for specific types and amounts of long lived low and intermediate level waste)
High level waste and spent fuel (if declared waste)	Content of long lived radionuclides above limits for short lived waste High thermal power	Geological disposal

3.2. DISPOSAL OPTIONS FOR DISUSED RADIOACTIVE SOURCES

Apart from certain types of radioactive sources, including some with very low concentrations of long lived radionuclides (e.g. smoke detectors) that can be disposed of in a dispersed fashion in landfills as exempt waste, disused radioactive sources are classified as either short or long lived low and intermediate level waste. However, for many repository operators disused radioactive sources represent a specific type of radioactive waste because of their high specific activity.

An important part of the safety assessment for a near surface repository is estimation of the dose from inadvertent intrusion scenarios. This will depend on the specific activity of the waste in the repository at the time of intrusion. In this context, higher activity radioactive sources in a disposal facility can continue to be ‘hot spots’ even after several hundred years, thus making them potentially unacceptable for near surface disposal.

Given this problem with the suitability of near surface repositories, other options may need to be considered for the disposal of disused radioactive sources. The choice of disposal system must be appropriate and commensurate with both the strengths and the half-lives of disused sources.

The wide range of activities described in Section 2.3 makes it convenient to classify radioactive source strengths as weak (<10 GBq), medium (10 GBq–10 TBq) or strong (>10 TBq). Higher activity and longer half-life sources obviously require a greater degree of isolation. Specifically, sources of particular concern for disposal are high activity sources containing ^{60}Co, ^{90}Sr, and ^{137}Cs, as well as long lived radium, americium and plutonium sources, because the half-lives of these radionuclides are longer than the period over which many engineered containment features will be effective. Hence the choice of a disposal system for these sources must be appropriate and commensurate with the half-life of the source. This could be provided by greater depth of disposal (that is, deeper than the 30 m normally associated with near surface disposal), with or without enhanced engineering. This is illustrated schematically in Fig. 5, which shows generic isolation options as a function of source strength plotted against the half-life of the source, and in Table 4.

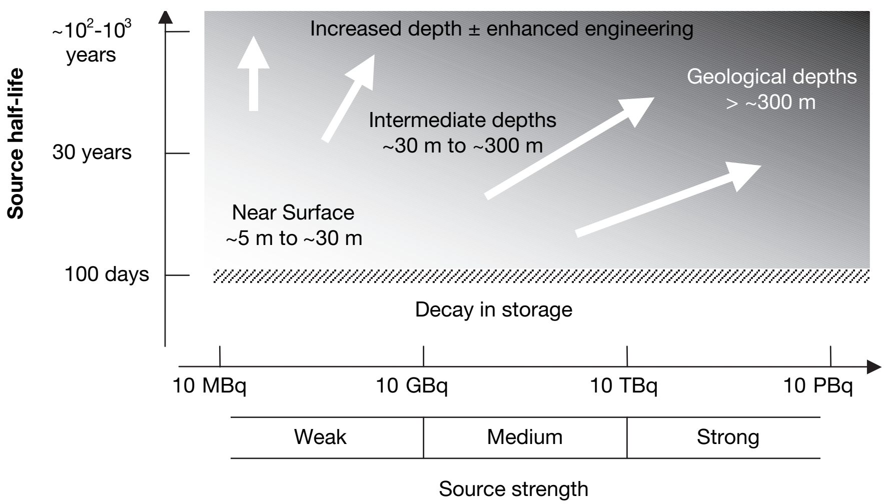

FIG. 5. Possible options for disposal of radioactive sources, making use of increased depth, with or without enhanced engineering, for stronger and/or longer lived sources.

TABLE 4. POSSIBLE DISPOSAL OPTIONS FOR RADIOACTIVE SOURCES

Types of radioactive source	Decay in storage	Near surface disposal without special requirements	Near surface disposal with greater depth and/or barriers	Geological disposal
$T_{½}$ = <100 d (^{125}I, ^{192}Ir, etc.)	×			
$T_{½}$ = 100 d–30 a		×	×	
$T_{½}$ = >30 a (^{90}Sr[a], ^{137}Cs, ^{238}Pu, ^{63}Ni, ^{241}Am, ^{226}Ra, ^{239}Pu)			×	×

[a] Although the half-life of ^{90}Sr is less than 30 years it is placed in this group because of its high activity.

Consideration of greater depths and the use of or enhancement of engineered barriers raises the possibility of using intermediate depth and deep geological repositories. The former are already available in some countries with nuclear power programmes and the latter are expected to be developed in the coming decade. Member States with such existing or planned facilities might consider these for disposal of some types of radioactive sources.

Countries that have no other nuclear activities must also manage inventories of radioactive sources safely. Some of these countries have very limited nuclear facilities and there is an urgent need to ensure long term control of disused radioactive sources. These countries might wish to consider shared solutions. Multinational cooperation appears to be a logical approach for disposal of disused radioactive sources for countries without a nuclear industry. In such situations dedicated regional or multinational facilities intended only for disposal of radioactive sources might be considered [30, 31]. These might also be appropriate for other Member States with nuclear power programmes (see Section 4).

The specific options that can be considered for the disposal of disused radioactive sources are shown schematically in Fig. 6 in terms of various combinations of depth, use of engineered barriers and overall design (i.e. trenches, vaults, caverns, shafts, boreholes, etc.). Shallow facilities are generally located at less than about 30 m depth [32], deep facilities generally at depths greater than about 300 m (depths generally associated with geological repositories) and intermediate depth facilities in the range from about 30 to 300 m below the surface. These depths only serve as examples, as site specific conditions and safety assessment will dictate the actual facility depth and the need for, and any requirements of, an engineered barrier system (EBS).

An EBS operating under stable and favourable geospheric conditions is normally designed to contain most of the radionuclides until the majority of the radioactivity has decayed in situ [33]. The specific role that an EBS is designed to play in a particular waste disposal concept is dependent on the conditions that are expected (or considered possible) to occur over the period of regulatory interest and the anticipated performance of the natural geological barrier. To be effective, an EBS must be tailored to the specific environment in which it is to function. Possible components of an EBS for disposal of radioactive sources are discussed in Section 3.2.6. In all disposal concepts, the natural geological and engineered barriers work together to provide passive isolation. The disposal options discussed above and shown in Fig. 6 are described in more detail in the following sections.

3.2.1. Option 1: Decay and disposal as exempt waste

Very low activity radioactive waste and exempt waste are often acceptable for disposal in landfill sites used for domestic and industrial wastes. National regulations set activity concentration levels for such wastes. Certain types of radioactive sources, including some with very low concentrations of long lived radionuclides (e.g. smoke detectors), can be disposed of in a

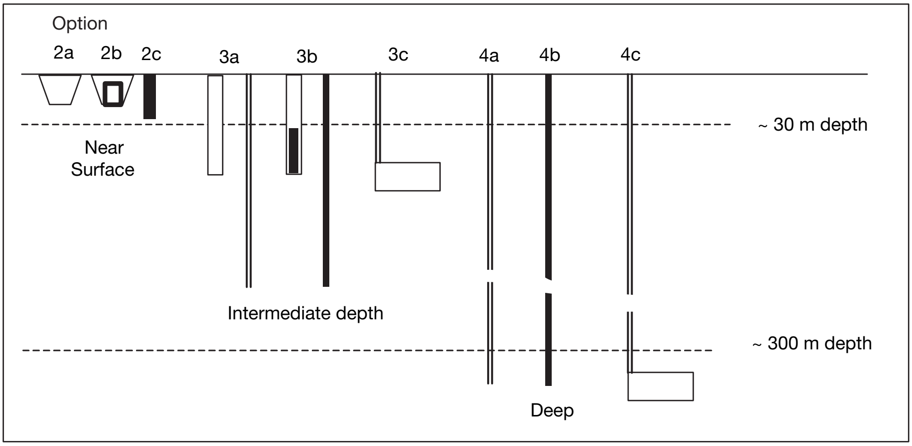

FIG. 6. Conceptual options suitable for the disposal of disused radioactive sources. Option 1 (decay and disposal as exempt waste) is not shown.

dispersed fashion in landfills as exempt waste. Bulk disposal of such sources in packages is generally not acceptable.

3.2.2. Option 2a: Simple near surface facilities

Simple trenches have been used for many decades for the disposal of short lived low and intermediate level wastes. They are generally considered appropriate only for those wastes that will decay sufficiently in situ within an anticipated period of institutional control (generally between 100 and 300 years) to represent no risk to the public, as determined by safety assessments. The design and function of such repositories are described in Refs [25–27].

This option would generally only be available for disposal of disused radioactive sources in countries with existing disposal facilities. As indicated in the previous section, this option is only suitable for lower activity sources which will have decayed to safe levels during the institutional control period. The objective is to ensure that after this period any radioactive sources in the repository do not constitute hot spots of activity that could present a hazard if the site is excavated or intruded into.

3.2.3. Option 2b: Engineered near surface facilities

Large scale (typically thousands of cubic metre capacity) near surface engineered vault repositories have similar containment objectives and are used for similar types of nuclear industry wastes as simple trenches (option 2a). Their engineering is intended to allow ease of waste emplacement and increased efficiency in the management and closure of the repository. As with option 2a, the design and function of such repositories are described in Refs [25–27]. They would generally only be available to countries with existing disposal facilities. From the viewpoint of disused radioactive source disposal there is little distinction between option 2a and large engineered vaults, as the issue of post-institutional control intrusion can still be a dominant factor in waste acceptability.

For the near surface disposal option, a performance assessment is also required to determine either that the activity of the radioactive sources can be contained until it has decayed or, if some migration is anticipated, that consequent doses are acceptable. Since any near surface facility used for disposal would be an existing licensed facility, this analysis would be based upon that used for the full repository.

If no repositories are available or are likely to become available in the near future, provision can be made for disposal of radioactive sources in facilities specifically designed to accommodate the generally small volume of radioactive sources. These will have varying levels of engineered containment matched to the characteristics of the radioactive sources they are to hold and are discussed in the following sections.

3.2.4. Option 2c: Near surface borehole or shaft facilities

Near surface shafts and/or boreholes can be considered as alternative or complementary to near surface vaults. These disposal options have the advantages of being economical and also minimizing the probability of human intrusion. If necessary an EBS can be added to the design and construction of these facilities to provide additional protection against radionuclide migration and human intrusion. More heavily engineered near surface facilities have been designed with the specific intention of reducing the likelihood of intrusion by emplacement of a massive concrete plug or cover over a large shallow shaft or borehole. For example, a reinforced concrete slab at least one metre thick is considered to be a deterrent to inadvertent intrusion. These intrusion resistant designs [26] will be helpful if institutional controls break down before the typically envisaged 300 year period. However, they do not offer a sufficient guarantee against intrusion to be considered for disposal of higher activity or longer lived sources than those suitable for disposal in near surface repositories.

3.2.5. Option 3a: Intermediate depth shafts or boreholes without EBSs

Disused or spent radioactive sources (SRSs) that are not acceptable for disposal in near surface disposal facilities because they will not decay sufficiently within the period of institutional control, may be suitable for disposal at greater depth in disposal units characterized by one of several configurations. At present, with the exception of deep tunnels and mines, it is uncommon to find construction work (e.g. deep foundation engineering) carried out at depths greater than about 30 m [32], so disposals at depths greater than this are only vulnerable to intrusion by deep drilling for water or mineral exploration — a much lower probability. As a result the intrusion exposure risks posed by high activity sources disposed of at intermediate depths are small.

Shafts or boreholes to depths of several tens of metres or more are relatively simple to construct and can offer an attractive disposal option for small volumes of waste such as radioactive sources [34–36]. Safety assessment may show that adequate safety can be achieved without the emplacement of EBS in addition to those contained in the disposal packages. It is anticipated that such relatively favourable situations might occur in conditions of limited or no contact between percolating water and the radionuclides contained in the disposal packages. If no existing or planned repository for other radioactive wastes is available, it appears logical that such an emplacement methodology (or its extension, option 3b, with an EBS) would be a relatively clear choice for a Member State with only radioactive sources to dispose of. Given the specific relevance of this option, the annex to this report looks at shaft and borehole disposal in more detail.

Shafts or boreholes excavated in arid environments in the unsaturated zone (above the water table) can offer adequate containment in the absence of additional EBSs. Examples of such disposal units are the shafts at the Greater Confinement Disposal Facility, Nevada Test Site in the USA [35], and at the Australian facility at Mt. Walton East [36]. Evaluation of such options needs to consider the stability of the hydrogeological system over the time period of concern for containment, which may be several hundreds or thousands of years depending on the types of radioactive sources to be disposed of.

Very low permeability host rocks, with little or no advection of groundwater, can also provide adequate containment without the need for additional EBSs. Some clay and claystone formations at intermediate depths can provide such an environment, and evidence of lack of flow can be obtained from pore water environmental isotope analyses and evaluation of any fracturing that may be present in the rock.

The isolation capability of this option depends on the ability to provide good shaft or borehole backfilling and sealing. The use of natural materials that reconstitute the original properties of the penetrated rock formations is recommended for all or some part of the sealing system. This may involve removal of some lining or casing to allow sealing against the host formations.

3.2.6. Option 3b: Intermediate depth shafts or boreholes with EBSs

If the disposal borehole/shaft is subject to significant water inflow or the geotechnical characteristics of the geological materials do not allow the excavation to be sufficiently stable, an EBS needs to be emplaced to provide a level of containment commensurate with the hazardous life of the waste.

The EBS is emplaced during the construction, operation or closure of a disposal unit and may consist of various components, shown schematically in Fig. 7. Table 5 shows the typical containment functions of possible EBS components for use in boreholes and shafts [37].

Waste containers and packages are important elements in the EBS and need to be designed to complement the other elements of the containment system, both human-made and natural. The design of containers and packages should be closely related to the definition of waste acceptance criteria for the

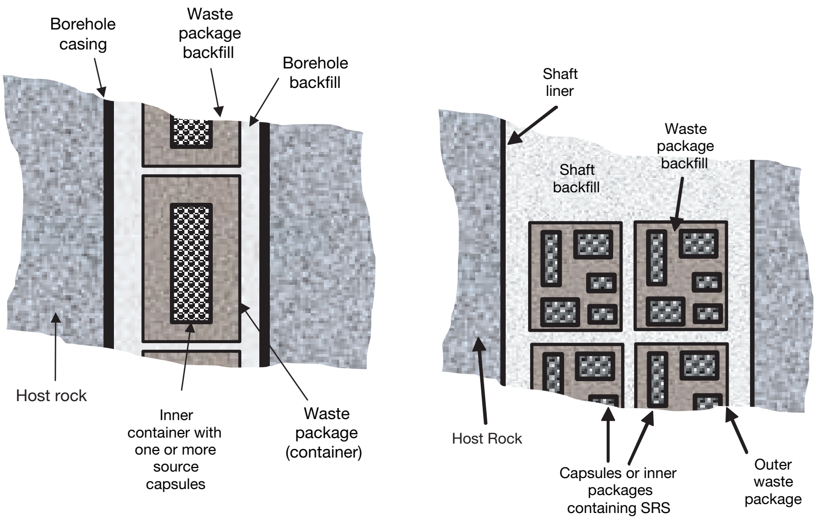

FIG. 7. Possible engineered barrier components in a borehole (left) or shaft (right) disposal facility.

specific disposal option. Waste packaging and conditioning considerations are discussed in Section 5.

It is important to note that the EBS does not need to include all the components listed in Table 5. The actual composition of the EBS has to be defined on the basis of the specific characteristics of radioactive sources and the geological environment. The requirements are essentially to use the right combination of materials and to enforce appropriate quality assurance measures.

3.2.7. Option 3c: Intermediate depth repositories

Some Member States (e.g. Sweden and Finland) have developed disposal facilities for radioactive waste in large rock cavities at depths of several tens of metres, generally in hard crystalline rocks such as granite. They are designed to contain short lived low and intermediate level waste. The containment provided by such repositories often comprises massive concrete vaults or silos, with additional EBSs such as clay backfills and buffers.

This type of containment would be adequate for the disposal of many if not all types of radioactive sources, so that countries having access to national or regional repositories could consider storing radioactive sources for eventual

TABLE 5. POSSIBLE COMPONENTS OF EBSs FOR USE IN BOREHOLE OR SHAFT DISPOSAL AND THEIR TYPICAL CONTAINMENT FUNCTIONS [37]

Component	Typical containment function
Original source capsule	Conservatively assume none (some sources may be damaged)
Welded metal (e.g. stainless steel) inner container for small sources (e.g. radium needles)	Containment of activity until failure due to corrosion from contact with pore water in borehole/shaft backfill or container backfill
Metal (e.g. mild or stainless steel) waste package or container holding several capsules	Containment of activity until failure due to corrosion from contact with pore water in borehole/shaft backfill
Package backfill in which sources may be embedded (e.g. cement grout)	Control corrosion rate of capsules Act as a sorption matrix for radionuclides released from sources Act as a diffusion barrier controlling movement of radionuclides out of packages
Borehole or shaft backfill surrounding the container (e.g. cement grout, natural soil or clay materials)	Control flow of water to waste packages and their corrosion rates Act as a sorption matrix or diffusion barrier controlling the movement of radionuclides out of packages
Metal or plastic borehole casing supporting borehole walls during drilling or emplacement operations, or concrete/steel shaft lining	Borehole casing can prevent access of groundwaters to waste packages until the casing is corroded or degraded Shaft lining is likely to have only a limited containment function
Seal: long (several metres) clay or cement plug placed above the disposal zone	Seal the waste disposal zone from shallower regions of the disposal system and prevent vertical short circuit release pathways

disposal, provided that legal and regulatory requirements on repository inventory permit.

For emplacement of high activity sources in a mined, intermediate depth repository it is necessary to consider packaging and activity concentrations that suit the thermal characteristics of the host rock and EBSs of the repository. In addition, disused mines and/or caverns can be considered for intermediate depth disposal.

3.2.8. Option 4a: Deep boreholes without EBSs

Such facilities have not been widely used for the disposal of radioactive waste. The objective of using deeper boreholes, at depths typical of geological repositories, would be to achieve greater isolation for limited volumes of radioactive waste, including disused radioactive sources, in an environment that is characterized by lower flow, more stable chemistry and longer potential return paths to the biosphere, compared with the other options. In a very low permeability environment (e.g. some clay and claystone formations), there may be no effective water movement at depths of a few hundreds of metres. In such conditions, provided an adequate borehole seal can be constructed, containment of radionuclides is provided by the geological barrier and there is no requirement for supplementary EBSs beyond those needed to emplace the radioactive sources into the borehole and to maintain borehole stability during emplacement operations (casing and cementing).

The option is particularly suited to the highest activity and long half-life radioactive sources, for which long containment periods are required (e.g. ~10–20 half-lives or more). For example, strong ^{226}Ra sources could require isolation for ~20 000 to 30 000 years. The depth and design of disposal also significantly reduce the likelihood of inadvertent intrusion, resulting in exposures to high concentrations of radionuclides before sources have decayed. If a facility of this type were developed for such sources it would also, of course, be technically suitable for the containment of any weaker, shorter half-life sources in the disposal inventory if this appeared to be a sensible solution economically and logistically.

3.2.9. Option 4b: Deep boreholes with EBSs

As with option 4a, such facilities have not been widely used for the disposal of radioactive waste. The objective would be the same, i.e. to remove radioactive sources to an environment that is characterized by lower flow, more stable chemistry and possibly longer return paths to the biosphere compared with the disposal options at shallow or intermediate depths.

In this option, additional EBSs are emplaced around the radioactive source containers so that adequate containment can be achieved in the higher flow environments encountered in more permeable geological formations. The typical components of an EBS are similar to those listed in Table 5. As with option 4a, if it appears to make economic and logistical sense, this route is also technically suitable for the containment of any weaker, shorter half-life sources in the disposal inventory.

3.2.10. Option 4c: Mined geological repositories

Mined repositories, comprising caverns or tunnels with varying types of EBSs, are being developed in many countries that have nuclear power industry wastes to manage. They are designed to contain long lived low and intermediate level waste, high level waste and spent fuel. The containment provided by all such repositories [23] would be more than adequate for the disposal of all types of radioactive sources, so that countries having access to a national or regional geological repository may consider storing all radioactive sources for eventual disposal, provided that legal and regulatory requirements on repository inventory permit (some countries have strict constraints on the types of waste that can be placed in specific repositories which are purely legal and unconnected with safety and performance). In addition, disused deep mines and/or caverns could be considered for geological disposal.

4. IDENTIFICATION AND SCREENING OF DISPOSAL OPTIONS

This section describes a simple process for screening the disposal options described in the previous section (shown in Fig. 6) and for identifying the most appropriate one(s). Consideration must be given to the entire disused source inventory. Consideration of only one type of disused source at a time may lead to the identification of a number of separate disposal options, whereas logistical and cost considerations may lead to the choice of one disposal option for the entire source inventory.

The process described in Fig. 8 leads to a preliminary identification of a disposal option. It does not consider additional factors such as the cost, available geological settings, complexity of site characterization, resources required to demonstrate site specific safety, public acceptance, transportation, occupational exposures and other factors that should be considered in making the final choice. Also, it does not include consideration of the alternatives that may be available when options are linked to potential disposal sites. Therefore the process in Fig. 8 is used only to identify and screen options for input to a broad decision making methodology.

In the first step all disused radioactive sources are identified and categorized according to their radiological properties, as discussed in Section 2. The key considerations in this step and subsequent steps are the half-life and strength of each source in the disposal inventory. Options for combining or

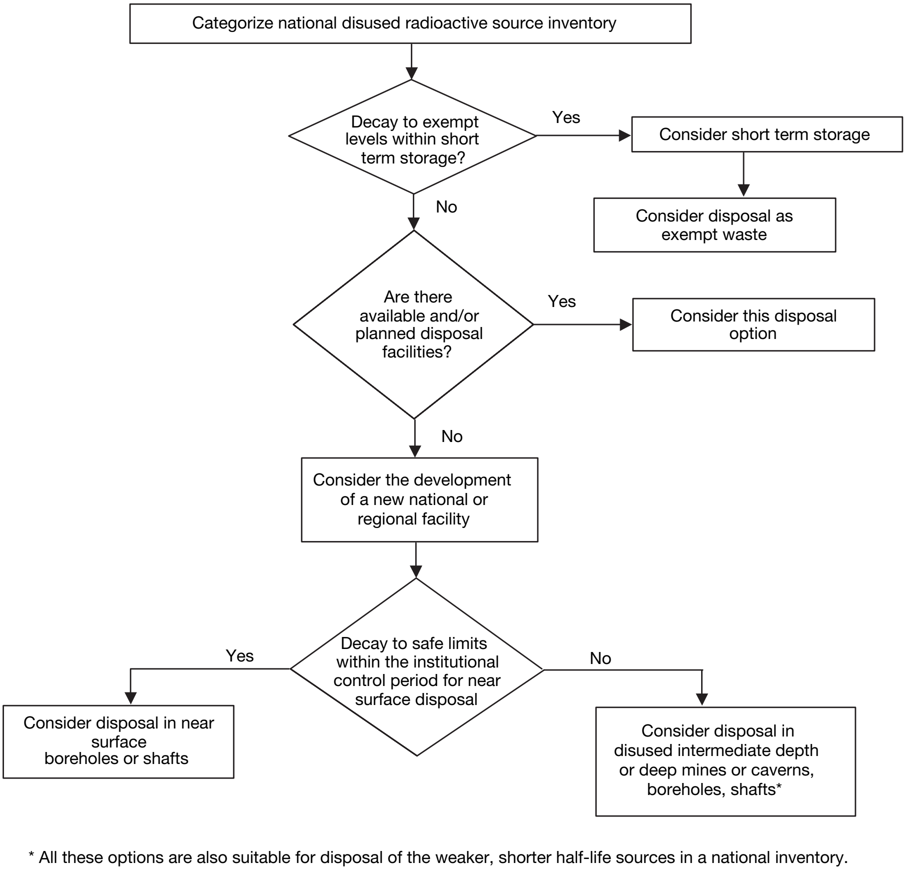

FIG. 8. Identification and screening of disposal options.

segregating types of sources to produce batched inventories should be considered if they can be designed to match a range of available disposal options.

Next, sources that may not require disposal in a waste disposal facility are identified on the basis of their half-lives and activities. These sources are those that could decay to safe levels during a relatively short period (a few tens of years) of monitored storage. Such storage would be followed by disposal as exempt commercial or industrial wastes according to national regulations and practices (option 1 in Section 3). Note that these sources could also be disposed of in existing near surface, intermediate depth or geological repositories.

Disused radioactive sources with longer half-lives and higher activities than those discussed above will require disposal as radioactive waste in licensed waste repositories. In considering a disposal option for these wastes disposal at existing or planned national facilities is preferable. Acceptance of waste at such disposal facilities depends on the repository's waste acceptance criteria, available disposal volume, cost of disposal and local societal considerations.

If no repositories are available or likely to become available in the near future, a new facility might be required to accommodate the generally small waste volumes associated with disused radioactive sources. In many countries radioactive materials are only used in industry, research and medicine. These countries might consider developing a dedicated national disposal facility for disused radioactive sources or, as part of a regional programme, a regional repository. In either case the remaining steps in this process of identifying and screening disposal options are the same.

The next step is to assess whether or not the remaining source inventory under consideration will decay to safe limits within the envisaged institutional control period for near surface facilities. In this publication it is assumed that all near surface disposal facilities are subject to a period of institutional control. Typical institutional control periods range from 100 to 300 years, but extended institutional control (e.g. to 500 years), or no control period, have also been used for some facilities. In practice, the duration of a site specific institutional control period must be established in consultation with authorities prior to making the decision on disposal options. Once the institutional control period has been established, an assessment can be made as to whether or not the source inventory will decay to safe limits within the designated time period. The definition of safe limits will depend on the facility's characteristics and the scenarios under consideration. For example, it may not be necessary for decay to reach exemption levels within the institutional control period but only to reach acceptable levels consistent with scenarios and exposure routes appropriate for the facility.

Near surface disposal is appropriate for those disused radioactive sources that will decay to safe limits within the institutional control period. Therefore, the next step in the process for those sources is to choose the type of near surface facility that is appropriate for the specific waste. The volume of waste to be disposed of is a key consideration at this stage. Disposal in shallow boreholes can be considered for small volumes of waste. On the other hand, if the total volume of waste is sufficiently large that it cannot be disposed of in shallow boreholes, consideration of disposal in shafts, with or without EBSs, may be necessary. These sources could also be disposed of in intermediate or deep disposal facilities.

For radioactive sources which will not decay to safe levels within the institutional control period, deeper disposal facilities that offer additional long term protection are needed. Again, the first option is to identify existing deeper facilities that may be usable for waste disposal. Disused mines and caverns may provide the degree of safety required for the sources. Such caverns and mines exist in a number of countries in environments which reduce the potential for migration into the biosphere.

Where disused mines and caverns do not exist, new facilities will have to be developed. Aside from safety a major consideration in the development of such a new facility is the minimization of cost and associated resources. For small volumes of waste, disposal in deeper boreholes may be the preferred option, as highlighted in Section 3 and described in more detail in the annex. If the total volume of all sources to be disposed of in a given country is small enough to fit within a single borehole, this deeper borehole solution will clearly make sense for the entire inventory.

If the volume of waste is too large to be disposed of in boreholes, consideration of disposal in shafts may be required (see Figs A–1 and A–2 in the annex). Shafts are essentially large boreholes. However, they are based on a different drilling technology and the costs associated with their development are greater than those for drilling boreholes.

Where a wide range of radioactive sources has to be disposed of in a given country, an efficient and flexible disposal facility may use several designs at the same site (see Section 3 and Fig. 6). For example, near surface pits or vaults and variable depth boreholes may be used at a single site. This solution may also be appropriate for countries that already have licensed near surface repositories at which these additional facilities for source disposal could be located. Radioactive source storage and conditioning facilities might also be located at the same disposal site.

5. WASTE PACKAGING AND ACCEPTANCE CRITERIA FOR DISPOSAL

Waste containers and packages are important elements of the EBS and as far as possible need to be designed in accordance with the other elements of the containment system, both human-made and natural. The design of containers and packages should be closely related to the definition of waste acceptance criteria for the specific disposal options.

Prior to disposal, disused radioactive sources are generally subjected to various management steps which may include storage, packaging and transport. These should be carried out so as to ensure that safety standards are met and that no breach of security is likely to take place. Radioactive sources present some specific issues in waste acceptance criteria. A radioactive source will usually contain a single radionuclide of known radioactivity and chemical form. The radioactive source will usually be contained in a special package which might or might not have a current certification. In many cases the radioactive sources will need to be further packaged prior to disposal to provide an assured longer term containment.

Packaging may have different purposes depending on the subsequent steps, for example to provide shielding during each handling step and during storage, to meet transport requirements and to prepare the sources for disposal. The intrinsic safety of the sources can also be enhanced by 'conditioning', for example by encapsulating them in cement or another solid matrix inside the waste package.

Conditioning and packaging reduce the potential for migration and dispersion of radionuclides during storage and disposal. In addition, they provide for better confinement of leaking sources. Although directed towards storage, the most comprehensive conditioning programme for disused radioactive sources is aimed at radium sources, as described in Refs [3, 38].

Once a decision is taken concerning the disposal of particular disused radioactive sources, their packaging needs to be assessed. Any existing packaging may be judged to be adequate or may need modification, based on the proposed disposal option. The design of disposal packages for radioactive sources is determined by operational and post-closure safety considerations and, if the disposal is to take place in disposal units with limiting dimensions (such as boreholes), by size limitations. Radioactive source packages that are acceptable for disposal with other waste types in existing or planned repositories (options, 2, 3c and 4c) would be expected to meet the relevant waste acceptance criteria for the disposal facility. The following considerations are thus relevant mainly for packaging and for developing waste acceptance criteria for dedicated disposal facilities — principally shafts and boreholes deeper than the near surface options.

Waste package size and design and the requirement for other engineered barriers will vary, depending on whether shaft or borehole disposal is selected, on the nature of the radioactive sources and on the isolation capacity of the host rock. These requirements need to be established by means of a facility specific operational and post-closure safety assessment.

5.1. DISPOSAL PACKAGE

A radioactive source package can contain one or more sources and comprise additional containment layers and any matrix material added to improve its overall properties. The external layer of the package may consist of metal, concrete or composite materials. Inside the package the disused radioactive sources can be placed within one or more additional containers or encapsulated in a conditioning matrix. Radioactive sources generally require shielding to ensure safety during storage and transport. In some cases the packaging may reduce external radiation levels sufficiently to allow for handling and transport. If not it may be necessary to use the original shielded containers or to design special packages. It is, however, clear that packaging for storage and transport has different requirements from packaging for disposal; for example, shielding is not generally an issue after disposal.

The waste container provides a fixed volume into which the disused radioactive sources can be emplaced and conditioned. At the time of disposal, transport packaging or shielding around the waste containers may be removed.

The package might be expected to contribute to the isolation of the radioactive sources by preventing or limiting the release of radionuclides into the geosphere. Two approaches can be applied to ensure longevity of the containment: use of corrosion resistant materials, or use of a thick walled container that would require a sufficiently long time to corrode. In both cases the effects of the physical and geochemical environment in the disposal zone play an important role.

The matrix (backfill) in which the radioactive sources are immobilized will have a significant effect on the properties of the package and can strongly influence its required performance.

5.2. PACKAGE DESIGN REQUIREMENTS

In order to perform the functions described above, the disposal packages need to meet specific design requirements, a detailed discussion of which can be found in Ref. [3].

5.2.1. Handling

Handling requirements during various stages of the disposal operations have a significant effect on the features and properties of the disposal package. This includes the following:

(a) Package shape and dimensions: For facilities with large access routes and disposal units no specific requirements are anticipated. For disposal in shafts, and particularly in boreholes, the shape and dimensions of the packages are determined by the borehole diameter and a cylindrical shape is preferable for the disposal packages. In order to ensure that the packages can be lowered into boreholes that might not be perfectly straight, there should be a gap between the internal diameter of the borehole and the package. This gap would also allow introduction of borehole backfill if this is considered necessary. As boreholes might not be vertical or straight, disposal packages should be relatively short to limit the risk of their getting stuck.
(b) Lifting arrangements: Packages should have lifting features compatible with available equipment. Their shape and strength should be defined.
(c) Package weight: Restrictions on package weight are mainly to avoid problems during handling. Weight restrictions are not anticipated to have an impact on the disposal concept.
(d) Stackability: If packages need to be stacked, they must be able to withstand the resulting load.
(e) Impact resistance: The package is the main containment barrier, preventing accidental release of radionuclides prior to emplacement. It is therefore necessary for packages to be robust enough to withstand handling and emplacement. If transport packages are to be used for disposal they should have adequate mechanical properties.

5.2.2. Radiation protection

Radiation protection requirements on package design can be grouped into those for surface contamination and surface dose rate.

(a) Surface contamination: Contamination on the external surface of any package should be kept as low as practicable and in accordance with acceptable limits defined by waste acceptance criteria. It is, however, anticipated that if packages meet contamination limits for transport they should be acceptable for disposal.
(b) Surface dose rate: To be transported to a disposal facility radioactive source packages need to meet appropriate limits on external radiation. The limits can be met by the packages on their own or through the use of shielded transport overpacks. In case of disposal in repositories with large disposal units that allow access of workers, the level of external radiation would need to be limited using standard health physics procedures. For borehole disposal, the external radiation level of the disposal packages

would be an important consideration during emplacement from the operational safety point of view, but not after the packages are lowered into the disposal zone. If the radiation levels are very high, consideration of the thermal and irradiation effects on the surrounding materials might be necessary.

5.2.3. Identification

Each disposal package should have a unique identifying label. The durability of the label should be assured at least until the time of closure of the disposal unit. All technical data and quality assurance records need to carry a reference to this unique identifier.

5.2.4. Package material

The required components and characteristics of the waste package depend on the performance assessment of the disposal facility, taking into account the evolution of all barriers, natural and engineered, over the requisite containment period and the possible release mechanisms. In carrying out this assessment, properties that need to be considered in the selection of the package materials include the following:

(a) Durability: Mechanical properties, corrosion resistance and general degradation properties;
(b) Compatibility: The package materials must be compatible with the disused radioactive sources and with any internal backfill;
(c) Geochemical conditions: Concentrations of aggressive chemicals such as chloride and sulphate in groundwater, redox potential and pH conditions;
(d) Thermal properties: Decay heat of radionuclides contained in the disused radioactive sources;
(e) Radiation stability: The activity level of some disused radioactive sources can be very high and therefore the package material selected must be stable under high radiation conditions.

5.2.5. Package closure

Full consideration should be given to the effective sealing of the package because this has a significant influence on its long term performance. The major requirements are [3]:

(a) Containment of gaseous and particulate radioactive materials;

(b) Prevention of groundwater ingress and release of liquids;
(c) Avoidance of an elevated internal pressure due to gas generation or thermal effects;
(d) Avoidance of explosive gas mixtures in void spaces;
(e) Containment of radionuclides when emplaced in the disposal unit.

After closure the package should, if possible, be tested for leaks to ensure the containment of the radionuclides, at least prior to closure of the disposal unit. After repository closure it can be assumed that the welds of any steel components will be the first thing to fail as a result of a combination of potential overpressure by gas generation and corrosion of the welds by chloride attack.

5.2.6. Package backfill

The package backfill may play an important role in the performance of the disposal system. Its specific functions include the following:

(a) Physical and chemical containment of radionuclides;
(b) Providing a barrier between the primary containers (capsules) and aggressive chemicals (primarily chloride) that may cause their corrosion;
(c) Providing chemical buffering of the near field, which may limit the release of certain solubility limiting radionuclides to the geosphere;
(d) Providing a physical and chemical barrier through which any mobilized radionuclides must pass before release into the environment.

The extent to which part or all of the functions must be fulfilled is based on the performance assessment of the disposal facility. To fulfil the functions of the backfill material listed above, several requirements can be identified:

(1) Suitable backfill material for the small packages likely to be used for disposal in boreholes must flow freely and be easy to mix. This is important from a quality control point of view and also to ensure that the backfill will perform as required.
(2) It is recognized that it would be problematic to totally fill all voids; consequently, a limited amount of void space is acceptable as long as it does not adversely affect the performance of the disposal system. The amount of void space is related to the porosity of the backfill material and to any residual unfilled volume inside the package. Its influence can only be assessed through a performance assessment of the package within a specific disposal system. Low porosity of the container backfill is

desirable to improve the microstructure and to minimize the release of radionuclides.

(3) During the source conditioning process the backfill material may need to be emplaced so that the radioactive sources are in the centre of the package. In some disposal concepts, variable thickness of the backfill around the radioactive sources in the container might affect the performance of the package.

(4) It should help to preserve the chemical and physical properties of the radioactive sources.

(5) It should minimize the ingress of water.

(6) The backfill material should be selected to provide a combination of low permeability and high sorption capacity to enhance its effectiveness as a physical and chemical barrier.

(7) It would be desirable if the package backfill, despite its low permeability, were able to allow gases to vent.

5.3. WASTE ACCEPTANCE CRITERIA FOR RADIOACTIVE SOURCES

Waste acceptance criteria are predetermined specifications that constitute requirements for the waste form and waste packages for disposal in a specific facility. Determination of the waste acceptance criteria for a particular disposal option is based on the specific safety concept and a related safety case for the selected disposal facility. The safety case should address both operational and post-closure safety. For high activity sources, operational safety considerations rather than post-closure safety may define the limits on the radionuclide content of waste packages. The safety evaluation should give reasonable assurance that compliance with the waste acceptance criteria will allow the facility to meet the relevant safety standards at all stages.

Different kinds of disposal facilities are capable of providing different degrees of isolation, depending on the features of the site, the depth of the disposal zone and the nature of the engineered barriers contributing to waste isolation. Consequently, the waste acceptance criteria will vary from one facility to another. Regardless of the disposal option selected, waste acceptance criteria need to be established in accordance with international practice and procedures, e.g. those set forth in Refs [30, 39, 40], taking into account the specific features of the disposal option, waste and site characteristics.

A number of approaches may be used to derive quantitative waste acceptance criteria for disposal of disused radioactive sources. It is important that the chosen approach be relevant, adequate, understandable and credible.

A safety assessment is the approach recommended by the IAEA for determining the waste acceptance criteria for the disposal of all kinds of radioactive waste [39, 40].

Generally, both radioactive and non-radioactive components and their associated hazards need to be taken into account for establishing waste acceptance criteria. They are established on the basis of operational constraints, the site and the repository's characteristics (such as lithology, hydrogeology, geochemistry and depth of the disposal zone) and the engineering design. If disposal is planned at shallow depth, a particularly important factor is the anticipated duration of institutional controls, which determines the acceptable content and concentration of longer lived radionuclides. In practice, the waste acceptance criteria for disused radioactive sources, as for other types of radioactive waste, need to be defined in such a manner that the results of the operational and post-closure safety assessments conform to the applicable safety targets (e.g. dose constraints).

Radiological criteria for the protection of the workforce and the general public are established in national regulations. More specific criteria for the packaging of radioactive sources and for repository design may be established by the regulatory authority directly or by the implementing organization, but are subject to regulatory approval. These criteria would need to take account of both normal operations and accidental situations, and encompass all phases of the repository's life cycle. Aside from the regulations addressing radiological safety, other existing regulations in relevant areas need to be taken into account.

The maximum activity that will be accepted in a container must be determined from operational and post-closure safety assessments. As noted above, operational considerations may be more constraining for the packaging of some high activity sources, although for such sources radiation and thermal characteristics may also need to be considered in the post-closure assessment.

The disposal of disused radioactive sources and the use of engineered barrier materials that could present potential chemical hazards (e.g. heavy metals) also have to comply with applicable regulations, and their properties have to be taken into account in safety assessments.

Chemical, microbiological or radiolytic processes, may take place within the radioactive source package, giving rise to gas, heat and/or corrosion (with an accumulation of hazardous degradation products), depending on the characteristics of the package materials. Potential gas generation issues should be addressed at an early stage in the development of a disposal concept and the design of the disposal units [41–44].

Other important non-radiological waste acceptance requirements may include physical criteria relating to the packages, such as weight, volume or dimension limits, and container design features, including impact and corrosion resistance, as discussed above.

6. SUMMARY AND CONCLUSIONS

This report has discussed the full range of disposal options that may be used for all types of disused radioactive sources. It has provided a simple flowchart scheme to identify potential disposal options and a method to use for selecting one or more disposal options, so that Member States can decide on the most appropriate option for the management of their inventories of radioactive sources.

Only a small number of source types can be stored until they decay to exemption levels of activity. The remaining sources in a national inventory will require underground disposal. A significant number will not decay to safe levels within the conventional institutional control period being advocated for near surface repositories, which means that most Member States will need to consider deeper disposal for their longer lived and higher activity sources. Consequently, although it may be possible to find solutions for some sources in a national inventory, a disposal facility located at intermediate depths (several tens of metres) or depths normally associated with geological disposal (hundreds of metres) is likely to be necessary for the remaining source inventory.

Intermediate depth or deep geological repositories may eventually become available options for some countries, and disposal in an existing or planned repository would clearly be the optimum solution for countries that have such facilities, provided site specific waste acceptance criteria can be met and the solution is cost effective.

A different focus is required for those countries that will not have access to such facilities and which must consequently develop their own national or shared multinational repositories. Due to the relatively small volume of disused source inventories, disposal units characterized by small dimensions, such as boreholes and shafts, have been discussed in particular detail, as has the possibility of adapting a disused mine or cavern, provided it can be adequately closed and sealed after disposal. Such disposal options have, to date, received much less attention in IAEA publications than other types of disposal facilities.

The borehole disposal option is particularly attractive in that it has a number of potentially favourable technological and safety features. Apart from the much lower cost, it is relatively easy to implement, allows modular application and a great deal of flexibility in design, has no large initial investment and infrastructure requirements, and is less intrusive on the landscape than a mined repository. The underlying common characteristic of all borehole facilities is their small cap area (footprint) at the surface, which reduces the likelihood of human intrusion into such a facility. Because of the unique design features, in particular the depth flexibility and small footprint, a borehole type facility has the potential to safely dispose of all types of radioactive sources and will require minimal post-closure controls. The difficulty of retrieving waste from a borehole facility would also contribute significantly to permanently eliminating the security threat posed by high activity and long lived disused radioactive sources.

The disposal of disused sealed radioactive sources in boreholes or shafts might offer long term safety and security for many countries with small inventories, and can offer significant advantages over more conventional near surface and intermediate depth disposal options.

Factors to be considered in reaching a decision on a disposal concept include:

(a) The inventory of disused radioactive sources that requires disposal and the likely future arisings of sources that may need to be disposed of;
(b) The national infrastructure for managing radioactive materials;
(c) Regulatory requirements governing the disposal of radioactive materials;
(d) Possible arrangements or the potential for sharing disposal solutions on a regional basis;
(e) The geological environment of the region with respect to potential disposal solutions;
(f) The technical and financial resources available for disposal;
(g) Social, political and ecological issues.

In order for it to be authorized by the appropriate regulatory authorities, it will have to be demonstrated that the proposed facility meets relevant safety requirements. Development and presentation of a convincing safety case will provide assurance to decision makers and the general public that a particular disposal concept for disused radioactive sources is capable of meeting the relevant safety objectives both at present and in the future.

The disposal of disused radioactive sources is an acceptable and safe long term management strategy. Although the preferred strategy is return the source to a supplier or recycle, most Member States have inventories of disused radioactive sources for which the only long term solution is disposal.

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REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Nature and Magnitude of the Problem of Spent Radioactive Sources, IAEA-TECDOC-620, IAEA, Vienna (1991).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Code of Conduct on the Safety and Security of Radioactive Sources, IAEA/CODEOC/2004, IAEA, Vienna (2004).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Handling, Conditioning and Storage of Spent Sealed Radioactive Sources, IAEA-TECDOC-1145, IAEA, Vienna (2000).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Management for the Prevention of Accidents from Disused Sealed Radioactive Sources, IAEA-TECDOC-1205, IAEA, Vienna (2001).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Spent High Activity Radioactive Sources (SHARS), IAEA-TECDOC-1301, IAEA, Vienna (2002).

[6] EUROPEAN COMMISSION, Management and Disposal of Disused Sealed Radioactive Sources in the European Union, Rep. EUR 18186 EN, EC, Luxembourg (2000).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, INFCIRC/546, IAEA, Vienna (1997).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Principles of Radioactive Waste Management, Safety Series No. 111-F, IAEA, Vienna (1995).

[9] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANISATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996).

[10] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Radiation Protection Recommendations as Applied to the Disposal of Long Lived Solid Radioactive Waste, Publication 81, Pergamon Press, Oxford and New York (2000).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Radiation Sources and Security of Radioactive Materials (Proc. Int. Conf. Dijon, 1998), IAEA, Vienna (1999).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Radioactive Waste Management (Proc. Int. Conf. Córdoba, 2000), IAEA, Vienna (2000).

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Issues and Trends in Radioactive Waste Management (Proc. Int. Conf. Vienna, 2002), IAEA, Vienna (2003).

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Security of Radioactive Sources (Proc. Int. Conf. Vienna, 2003), IAEA, Vienna (2003).
[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Categorization of Radioactive Sources, IAEA-TECDOC-1344, IAEA, Vienna (2003).
[16] INTERNATIONAL ATOMIC ENERGY AGENCY, The Radiological Accident in Gilan, IAEA, Vienna (2002).
[17] INTERNATIONAL ATOMIC ENERGY AGENCY, The Radiological Accident in Lilo, IAEA, Vienna (2000).
[18] INTERNATIONAL ATOMIC ENERGY AGENCY, The Radiological Accident in Goiânia, IAEA, Vienna (1988).
[19] INTERNATIONAL ATOMIC ENERGY AGENCY, The Radiological Accident in Tammiku, IAEA, Vienna (1998).
[20] INTERNATIONAL ATOMIC ENERGY AGENCY, The Radiological Accident in Samut Prakarn, IAEA, Vienna (2002).
[21] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of Radioactive Waste, Safety Series No. 111-G-1.1, IAEA, Vienna (1994).
[22] INTERNATIONAL ATOMIC ENERGY AGENCY, Near Surface Disposal of Radioactive Waste, IAEA Safety Standards Series No. WS-R-1, IAEA, Vienna (1999).
[23] INTERNATIONAL ATOMIC ENERGY AGENCY, Issues Relating to Safety Standards on the Geological Disposal of Radioactive Waste (Proc. Mtg Vienna, 2001), IAEA-TECDOC-1282, IAEA, Vienna (2002).
[24] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment for Near Surface Disposal of Radioactive Waste, IAEA Safety Standards Series No. WS-G-1.1, IAEA, Vienna (1999).
[25] INTERNATIONAL ATOMIC ENERGY AGENCY, Considerations in the Development of Near Surface Repositories for Radioactive Waste, Technical Reports Series No. 417, IAEA, Vienna (2003).
[26] INTERNATIONAL ATOMIC ENERGY AGENCY, Technical Considerations in the Design of Near Surface Disposal Facilities for Radioactive Waste, IAEA-TECDOC-1256, IAEA, Vienna (2001).
[27] INTERNATIONAL ATOMIC ENERGY AGENCY, Scientific and Technical Basis for the Near Surface Disposal of Low and Intermediate Level Waste, Technical Reports Series No. 412, IAEA, Vienna (2002).
[28] INTERNATIONAL ATOMIC ENERGY AGENCY, Legal and Governmental Infrastructure for Nuclear, Radiation, Radioactive Waste and Transport Safety, IAEA Safety Standards Series No. GS-R-1, IAEA, Vienna (2000).
[29] INTERNATIONAL ATOMIC ENERGY AGENCY, Socio-economic and other Non-radiological Impacts of Near Surface Disposal of Radioactive Waste, IAEA-TECDOC-1308, IAEA, Vienna (2002).
[30] INTERNATIONAL ATOMIC ENERGY AGENCY, Technical, Institutional and Economic Factors Important for Developing a Multinational Radioactive Waste Repository, IAEA-TECDOC-1021, IAEA, Vienna (1998).

[31] INTERNATIONAL ATOMIC ENERGY AGENCY, Developing Multinational Radioactive Waste Repositories: Infrastructural Framework and Scenarios of Cooperation, IAEA-TECDOC-1413, IAEA, Vienna (2004).

[32] OECD NUCLEAR ENERGY AGENCY, Shallow Land Disposal of Radioactive Waste: Reference Levels for the Acceptance of Long-lived Radionuclides. A Report by an NEA Expert Group, OECD, Paris (1987).

[33] OECD NUCLEAR ENERGY AGENCY, Engineered Barrier Systems (EBS) in the Context of the Entire Safety Case (Proc. Workshop Oxford, 2002), OECD, Paris (2003).

[34] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Considerations in the Disposal of Disused Sealed Radioactive Sources in Borehole Facilities, IAEA-TECDOC-1368, IAEA, Vienna (2003).

[35] COCHRAN, J.R., et al., Compliance Assessment Document for the Transuranic Wastes in the Greater Confinement Disposal Boreholes at the Nevada Test Site, Vol. 2: Performance Assessment, Rep. Sand 2001-2977, Sandia National Laboratories, NM (2001).

[36] HARTLEY, B.M., et al., "The establishment of a radioactive waste disposal facility in Western Australia for low level waste", Nuclear Energy, Science & Technology (Proc. 9th Pacific Basin Nucl. Conf. Sydney, 1994), AE Conventions Pty Ltd, Canberra (1994).

[37] SOUTH AFRICAN NUCLEAR ENERGY CORPORATION, Design for the Borehole Disposal Concept, Rep. GEA 1623, NECSA, Pretoria (2003).

[38] INTERNATIONAL ATOMIC ENERGY AGENCY, Conditioning and Interim Storage of Spent Radium Sources, IAEA-TECDOC-886, IAEA, Vienna (1996).

[39] INTERNATIONAL ATOMIC ENERGY AGENCY, Qualitative Acceptance Criteria for Radioactive Wastes to be Disposed of in Deep Geological Formations, IAEA-TECDOC-560, IAEA, Vienna (1990).

[40] INTERNATIONAL ATOMIC ENERGY AGENCY, Derivation of Activity Limits for the Disposal of Radioactive Waste in Near Surface Disposal Facilities, IAEA-TECDOC-1380, IAEA, Vienna (2003).

[41] OECD NUCLEAR ENERGY AGENCY, Gas Generation and Release from Radioactive Waste Repositories (Proc. Workshop Aix-en-Provence, 1991), OECD, Paris (1992).

[42] NUCLEAR REGULATORY COMMISSION, Microbial Degradation of Low-Level Radioactive Waste, Rep. NUREG/CR-6341, Office of Standards Development, NRC, Washington, DC (1996).

[43] EUROPEAN COMMISSION, PROGRESS Project: Research into Gas Generation and Migration in Radioactive Waste Repository Systems. Final Report, Rep. EUR 19133 EN, EC, Luxembourg (2000).

[44] OECD NUCLEAR ENERGY AGENCY, Gas Generation and Migration in Radioactive Waste Disposal (Proc. Workshop Reims, 2000), OECD, Paris (2001).

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Annex

BOREHOLE DISPOSAL

Boreholes and shafts to depths of several tens of metres and boreholes to depths of some hundreds of metres are relatively simple to construct and may offer an attractive disposal option for Member States, especially if they have only radioactive sources to dispose of. The depth of disposal boreholes can vary greatly, depending on a variety of specific factors such as the characteristics of the sources (e.g. activity and longevity of radionuclides), technical features of the engineered barriers (e.g. corrosion resistance of package materials and nature of the backfill), and properties of the surrounding geological medium (e.g. hydrogeological and geochemical characteristics). It is anticipated that in most cases borehole depths of the order of tens of metres may be adequate, but there is no conceptual reason to prevent the use of boreholes from reaching depths of hundreds of metres, that is in the depth range typical of geological repositories.

Widely available drilling technologies provide adequate technical tools for implementation of the borehole disposal concept. The drilling methods may vary depending on the depth and diameter of the borehole, type of geological formation to be penetrated, cost, and other considerations.

Apart from depth, special features of the borehole disposal option that contribute to the confinement and isolation of radionuclides include robustness of design and the characteristically small ratio of cap area to disposal volume. Depth provides inaccessibility from intrusion and protects the radioactive sources from infiltration of rainwater, and from climatic and other dynamics and near surface phenomena. Design features of both the source packages and the disposal units prevent or limit radionuclide release. Additionally, the relatively small footprint of boreholes limits vulnerability to the potential exposure of wastes in case of cap failure caused by differential settling, erosion and human activity, as well as inadvertent intrusion.

Safety assessment may show that adequate safety can be achieved in such facilities without the emplacement of EBSs additional to those contained in the disposal packages. It is anticipated that such relatively favourable situations might occur in conditions of limited or no contact between percolating water and the radionuclides contained in the disposal packages. If no existing or planned repository for other radioactive wastes is available, such an emplacement methodology or its extension using an EBS may be the most desirable option. Therefore this annex looks at borehole and shaft disposal in more detail.

The borehole disposal option is particularly attractive in that it has a number of potentially favourable technological and safety features. Apart from its much lower cost it is relatively easy to implement, allows modular application and a great deal of flexibility in design, has no large initial investment and infrastructure requirements, and is less intrusive on the landscape than a mined repository. The underlying common characteristic of all borehole facilities is their small footprint at the surface, which reduces the likelihood of human intrusion into such a facility. Because of the unique design features, in particular the depth flexibility and small footprint, a borehole type facility has the potential to safely dispose of all types of radioactive sources and will require minimal post-closure control. This option is particularly suited for the higher activity and longer lived sources, where a long containment period is required (e.g. about 10 to 20 half-lives or more, which for ^{226}Ra sources implies containment times of a few tens of thousands of years). The depth of disposal also significantly reduces the likelihood of inadvertent intrusion that might result in exposures to high concentrations of radionuclides before the sources have decayed.

A borehole disposal facility may consist of a single borehole or a series of boreholes of varying depths, depending on the inventory and characteristics of the sources. Given the limited land area requirements, a borehole facility specifically designed for the disposal of radioactive sources also has the potential to be located with an existing nuclear facility. Campaign type disposals followed by immediate closure or gradual emplacement in an open borehole over several years are options that may be considered.

A recent IAEA report discusses the general considerations related to the safe disposal of disused radioactive sources and other limited quantities of radioactive waste in borehole type facilities [A–1].

The following examples illustrate the intermediate depth disposal option without an EBS (see Section 3.2.5 of the main text). Greater boreholes or shafts excavated in arid environments in the unsaturated zone (Figs A–1, A–2) can offer adequate containment in the absence of any additional engineered barriers. Examples of such disposal units are the shafts at the Greater Confinement Disposal Facility at the Nevada Test Site, USA (Fig. A–3) [A–2] and at the Australian facility at Mt. Walton East (Fig. A–4) [A–3]. An evaluation of such options needs to consider the stability of the hydrogeological system over the time period of concern for containment, which may be several hundreds or thousands of years depending on the source inventory to be disposed of.

The isolation capability of this option depends on the ability to provide good shaft or borehole backfilling and sealing. The use of indigenous natural materials

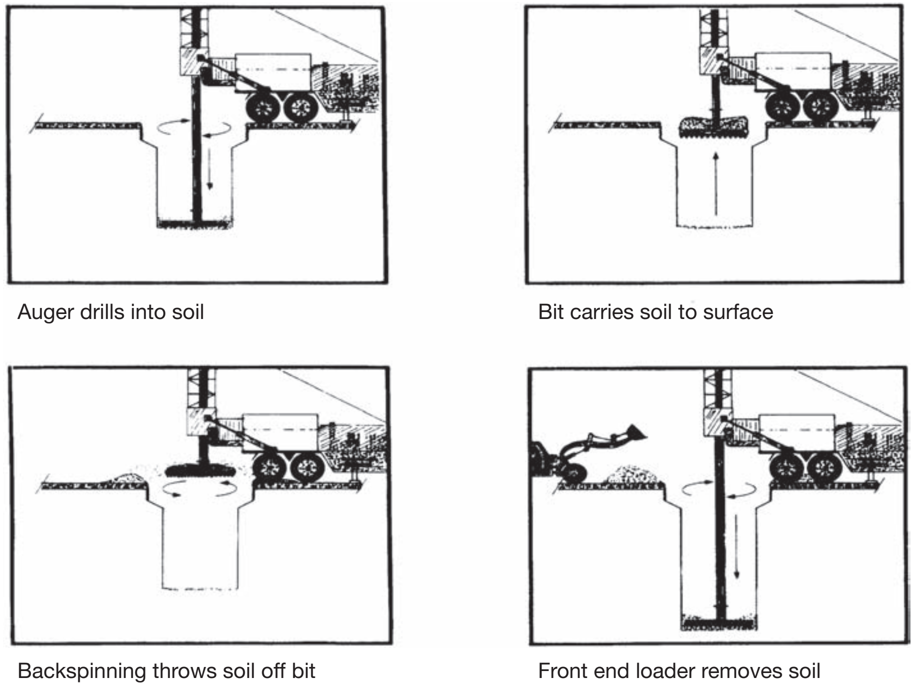

FIG. A–1. Drilling of a shaft at the Greater Confinement Disposal Facility at the Nevada Test Site, USA [A–2].

FIG. A–2. Drilling of a Greater Confinement Disposal Facility shaft [A–2].

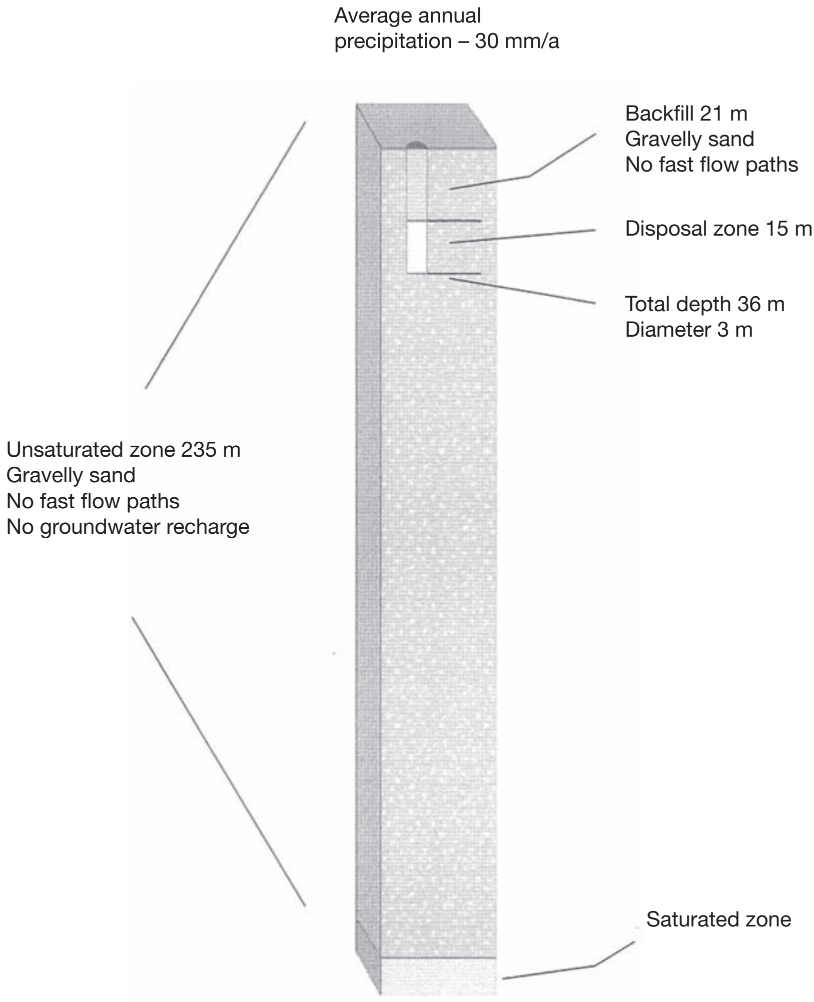

FIG. A–3. Cross-section of the Greater Confinement Disposal Facility at the Nevada Test Site, USA [A–2].

that reconstitute the original properties of the rock formations penetrated is recommended for all or part of the sealing system, and this may involve removal of some lining or casing to allow sealing against the host formations.

If the disposal borehole/shaft is subject to water inflow, or the geotechnical characteristics of the geological materials do not allow the excavation to be sufficiently stable, additional engineered barriers need to be emplaced. Plastic or metal borehole liners might be considered, along with a bentonite or

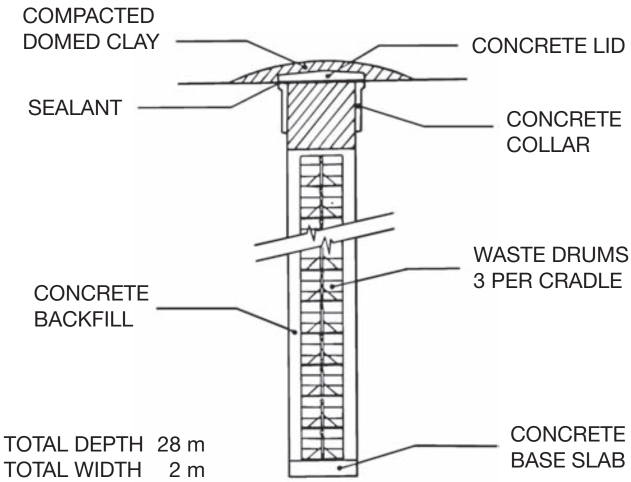

FIG. A–4. Borehole disposal at Mt Walton East, Australia [A–3].

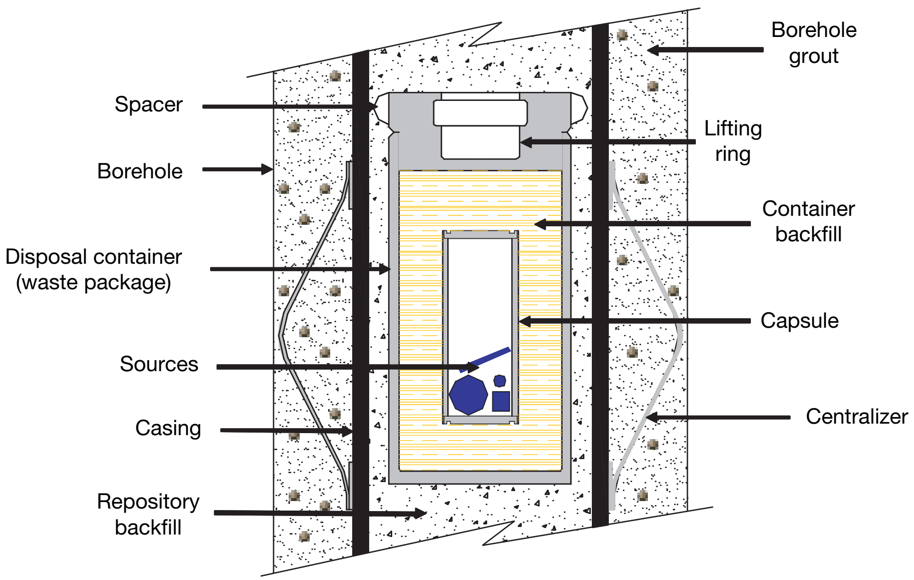

FIG. A–5. The NECSA borehole disposal concept for radioactive sources [A–4].

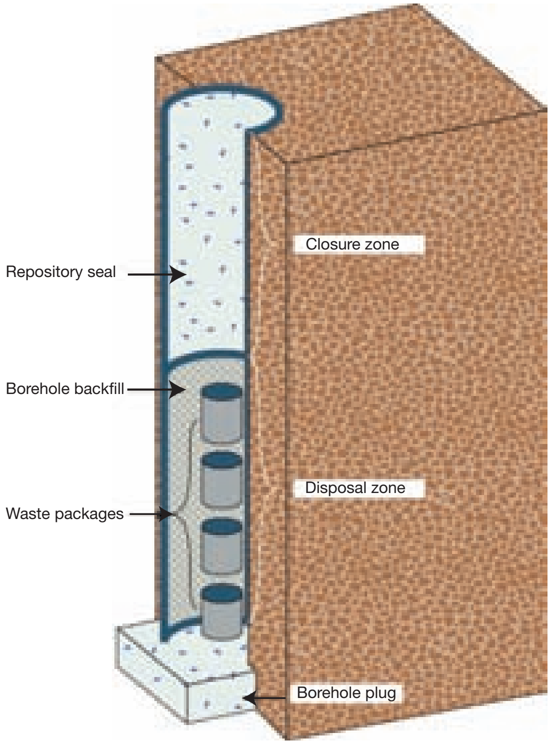

FIG. A–6. A conceptual borehole repository based on NECSA work [A–4].

grout borehole backfill. Again, sealing of the boreholes will be an important aspect to be considered in the safety evaluation.

The selection of borehole depth and design will depend upon the geological and hydrogeological environments available for siting, as well as on the inventory of radioactive sources to be disposed of. Some generic and site specific safety assessments have been carried out regarding the disposal of radioactive sources in boreholes. The positive results of the assessments indicate that disposal in boreholes and shafts can be considered a viable option for the disposal of radioactive sources and can offer significant advantages over more conventional near surface and intermediate depth disposal options.

Currently, an IAEA sponsored regional technical assistance project in South Africa is assessing the technical feasibility, safety and economic viability of the borehole concept for the disposal of disused radioactive sources in African countries [A–4]. Figure A–5 shows the borehole disposal concept developed by the South African Nuclear Energy Corporation (NECSA) in

South Africa. A conceptual borehole repository envisaged by NECSA is shown in Fig. A–6.

The design being considered utilizes 260 mm diameter boreholes drilled to about 100 m depth, with a 160 mm diameter inner casing. The waste packages under development, which may be constructed of stainless steel, would be ~114 mm in diameter and ~230 mm long, allowing ease of emplacement. An inner stainless steel capsule would contain the radioactive sources and the packages would be backfilled with a cement grout. The waste packages would be emplaced about 1 m apart. The borehole would be backfilled with cement grout.

Given the unique design features of a borehole or shaft type repository compared to a conventional storage or disposal facility, the security of the emplaced waste would be considerably enhanced, making the waste less accessible and vulnerable to theft or for use as potential radiological dispersion devices for terrorism. The difficulty of retrieving waste from a borehole repository would also contribute significantly to permanently eliminating the security threat posed by high activity and longer lived sources.

REFERENCES TO THE ANNEX

[A–1] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Considerations in the Disposal of Disused Sealed Radioactive Sources in Borehole Facilities, IAEA-TECDOC-1368, IAEA, Vienna (2003).

[A–2] COCHRAN, J.R., et al., Compliance Assessment Document for the Transuranic Wastes in the Greater Confinement Disposal Boreholes at the Nevada Test Site, Vol. 2: Performance Assessment, Rep. SAND 2001-2977, Sandia National Laboratories, NM (2001).

[A–3] HARTLEY, B.M., et al., “The establishment of a radioactive waste disposal facility in Western Australia for low level waste”, Nuclear Energy, Science and Technology (Proc. 9th Pacific Basin Nucl. Conf. Sydney, 1994), AE Conventions Pty Ltd, Canberra (1994).

[A–4] SOUTH AFRICAN NUCLEAR ENERGY CORPORATION, Design for the Borehole Disposal Concept, Rep. GEA 1623, NECSA, Pretoria (2003).

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Following a review of potential disposal options for disused radioactive sources with various radiological contents, this report highlights the use of borehole or shaft type repositories as a possible disposal option, particularly for those countries that have limited resources and are looking for a simple, safe and cost effective solution for the disposal of their radioactive sources.

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