DISPOSAL OPTIONS FOR DISUSED RADIOACTIVE SOURCES

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ABSTRACT

This report presents the full range of disposal options that might be used for all types of disused radioactive sources, with special attention being paid to the technological features of the different options. It provides a simple scheme to help the owners of radioactive sources decide on the most appropriate disposal option for different types of sources, based upon their half-lives and their strengths. Disposal of radioactive sources in shafts or boreholes, apart from satisfying safety requirements and being attractive from an economic viewpoint, is considerably more flexible and modular, has no large initial investment demands and is less intrusive on the landscape than conventional disposal facilities. Since it also has similar or even better containment performance than other disposal options, disposal in shallow- and intermediate-depth boreholes has been practised or proposed for different types of radioactive waste in various countries and presently is being assessed internationally.

INTRODUCTION

A specific area of radioactive waste management of current interest is the management of disused radioactive sources. Sealed radioactive sources have been used globally in a wide range of applications in medicine, industry and research for more than a century. At the end of their useful life, the radioactive sources are defined as spent or disused. However, the residual level of radioactivity may still be quite high. Such disused radioactive sources could pose a potential health hazard to the public for periods that, depending on the half-life of the radionuclides, may extend to hundreds and thousands of years. The disused radioactive sources are simply another type of radioactive waste that needs to be disposed of safely.

The level of activity and their high concentration, plus the long half-life of some radionuclides, pose problems managing disused radioactive sources in the context of conventional waste management schemes in most countries. Some radioactive sources, which are long-lived and relatively high activity, do not fall in the category of short-lived or low-activity waste, normally acceptable for disposal in near surface repositories. This is because the institutional controls period may not be sufficiently long to allow the sources to decay to innocuous 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 most countries; a practice that is considered not sustainable in the long run and, in many cases, may represent a high-risk situation (1). Large inventories of disused radioactive sources exist in many countries, which have no other nuclear activities and, therefore, represent the only type of radioactive waste that needs to be managed safely.

During the past decade, the IAEA and its Member States, in particular in the European Union, have taken steps to lower the risks associated with disused radioactive sources and the likelihood of potential incidents and accidents. Various activities are being implemented to improve the management of disused radioactive sources in order to ensure that they are manufactured, handled, used, reused, transported, stored and disposed of in a technically sound, cost-effective and safe manner (2-4).

Although significant progress has been made in the management of low and intermediate level waste (LILW) and high level waste, the long term safety as well as security of disused radioactive sources continues to be a subject of concern, in particular their disposal is still a major topical issue at the international level (5-7). More recently, international concern about the safety and security of disused radioactive sources was highlighted at an International Conference hosted by the IAEA in Vienna, March 2003 (8). Although the Conference focused on the most immediate issues, such as the safe and secure storage of the sources, issues dealing with the long-term management, specifically disposal, were also raised in the context of developing a system of national and/or regional repositories for the safe disposal of these sources.

Given that disused radioactive sources exhibit a high degree of variability in their radiological properties, covering both high-activity sources that emit heat and radiation and sources that contain long-lived radionuclides, as well as low-activity and relatively short-lived sources, there is a wide spectrum of options potentially applicable to the disposal of radioactive sources, ranging from near surface and mined-cavern disposal facilities to geological repositories, including borehole-type facilities of varying depths. Depending on the source radiological properties and site characteristics, the available disposal options can involve an engineered barrier system, with varying levels of engineering, subjected to a range of environmental conditions.

The report discusses various options available for the disposal of disused radioactive sources, taking into consideration the high degree of variability in their radiological characteristics. The discussion focuses on the borehole disposal option and its potential application to the safe disposal of all categories of radioactive sources.

CATEGORIES OF RADIOACTIVE SOURCES

Table I provides a list of commonly-used radioactive sources, categorized according to the half-lives of the radionuclides.

Table I Categories of disused sealed radioactive sources

Radionuclide	**Half-life**	**Maximum Expected Activity (MBq)**	**Application**
Category 1	**Half-life < 100 days**		
Au-198	2.7 d	1.5.E+03	Manual brachytherapy
Y-90	2.7 d	5.0.E+02	Manual brachytherapy
I-131	8 d	1.5.E+03	Manual brachytherapy
P-32	14.3 d	2.0.E+02	Vascular brachytherapy
Pd-103	17 d	1.5.E+03	Manual brachytherapy
Sr-89	50.5 d	1.5.E+02	Vascular brachytherapy
I-125	60 d	1.0.E+04	Bone dosimetry
Ir-192	74 d	5.0.E+06	Industrial radiotherapy
Category 2	**100 days < Half-life ≤~30 years**		
Po-210	138 d	2.22E+03/ 9.25E+06	Static eliminators/ Well logging
Gd-153	242 d	1.11E+05	Bone dosimetry
Co-57	271.7 d	5.0E+05	Markers
Ru-106	1.0 y	5.0E+04	Manual brachytherapy
Cf-252	2.6 y	5.0E+03	Calibration facilities
Pm-147	2.62 y	5.0E+05	Sources as standards in instruments
Co-60	5.3 y	5.0E+04	Sterilization and food preservation
Kr-85	10.8 y	3.7E+05	Thickness gauge
H-3	12.3 y	5.0E+06	Tritium targets
Sr-90	29 y	5.0E+04	Thickness gauge
Cs-137	30.1 y	5.0E+05	Sterilization and food preservation
Category 3*	**Half-life >~30 years**		
Pu-238	87.7 y	3.7E+03	Static electricity removal
Ni-63	100 y	5.0E+02	Electron capture detector
Am-241/Be	433 y	8.0E+05	Well logging
Ra-226	1600 y	3.7.E+03	Manual brachytherapy
C-14	5 700 y	22.2	Device calibration
Cl-36	3.E+05 y	4.00	Sources as standards in instruments
I-129	1.6.E+7 y	4.00	Sources as standards in instruments

*In some countries, ^{239}Pu, used in smoke detectors, is a significant radionuclide in disused sealed sources, requiring disposal.

Radioactive sources in Category 1, having half-lives of less that 100 days, will decay to safe levels in a few years. From a waste management point of view, the category 1 sources can be safely allowed to decay in storage or in near surface disposal facilities. Category 1 sources are, however, not necessarily benign; for example, a mismanaged 185 GBq ^{192}Ir source led to a serious radiological accident in Iran in 1996 [9].

The inventory of Category 2 sources, with half-lives of less than 30 years, comprises primarily sources containing ^{60}Co, ^{137}Cs, and ^{90}Sr. These sources may be of significant strength. For example, ^{90}Sr sources found in radioisotopic thermoelectrical generators may contain in excess of 10 PBq per unit. With such high strengths and moderate half-lives, the Category 2 sources require isolation for hundreds to thousands of years.

The Category 3 sources, with half-lives of greater than 30 years, contain primarily 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. Category 3 sources may contain also ^{226}Ra. With half-lives ranging from 87 years for ^{238}Pu to 1,600 years for ^{226}Ra, Category 3 sources pose a potential health hazard for thousands of years. A particular type of Category 3 sources consists of those sources used for calibration of instruments; they may contain extremely long-lived radionuclides, such as ^{14}C (half-life = 5,700 years), ^{36}Cl (half-life = 3 E+05 years) and ^{129}I (half-life = 1.7 E+07 years), however, their activity is generally so low that it is of negligible radiological significance.

Data on radionuclides and their activities in radioactive sources have recently been reviewed by the IAEA [10]. The data provide minimum, maximum and typical activity levels in the sources. The maximum source activities for the various radionuclides versus radionuclide half-life are displayed in Fig. 1(a). Radioactive sources with the highest activity are ^{60}Co and ^{90}Sr and ^{137}Cs sources; same of these sources exceed 10PBq. Also shown in Fig. 1(a) are the exemption levels for total radioactivity, based on the Basic Safety Standards [BSS] for radionuclides found in the various radioactive sources.

All sources begin to decay from the time they are manufactured and this has a direct bearing on available disposal options. Fig. 1(b) shows the effect of 100 years' decay on the maximum source activities shown in Fig. 1(a). After 100 years' decay, all sources with a half-life of less than 5 years will have decayed to less than the exemption levels. Some ^{60}Co sources are still significantly above the exemption levels as are most of the longer-lived sources. Fig. 1(c) shows the range of activities after 300 years' decay where only radionuclides with equal to or longer than ^{90}Sr (29 years) are still significantly above the exemption levels and will thus continue to represent point sources of high activity if they were to be disposed in a near surface repository, even after the conventional institutional controls period. Nevertheless, since most Member States anticipate that institutional controls at the sites of near surface disposal facilities will be maintained for periods between 100 and 300 years, the data in Figs. 1(b) and 1(c) indicate that the disposal of radioactive sources in near surface repositories is safe for all Category 1 sources, a significant fraction of Category 2 sources, and for some low-activity sources in Category 3.

The comparison in Figs. 1(a), (b) and (c) uses the BSS radionuclide-specific exemption levels as an indicator that a source has no residual risk. In fact, the BSS exemption levels are a very conservative estimate of no risk and is based on unrestricted future use and exposure pathways. For a source in a repository, exposure pathways are very limited and the safety analyses for a specific repository could demonstrate acceptably low risk at an activity well above the BSS values.

It is important to notice that the above observations are generic in nature and that, in practice, the actual acceptance of radioactive sources in a disposal facility needs to be authorized by the regulatory body on the basis of a specific safety assessment.

(a)

(b)

(c)

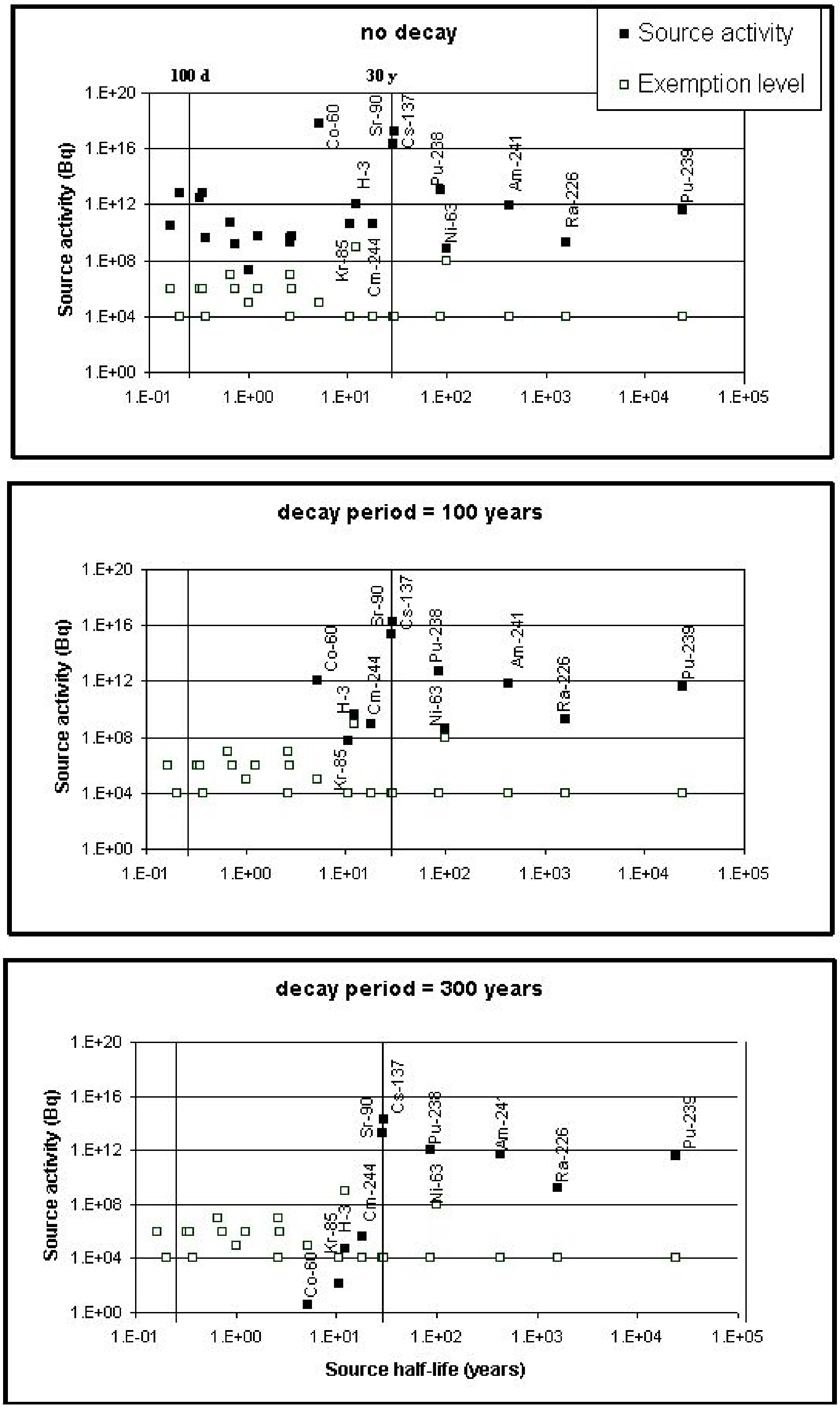

Fig. 1 Maximum source activities for various radionuclides:
(a) no decay; (b) decay period = 100 y; (c) decay period = 300 y

DISPOSAL CONSIDERATIONS FOR RADIOACTIVE WASTE

The IAEA classification of radioactive waste [11] provides a generic approach to radioactive waste management. Radioactive waste is categorized as exempt waste, short-lived LILW, long-lived LILW, and high level waste. Potential disposal options have been identified for each waste category, based on their specific characteristics, with the concentrations and longevity of the radioactive waste components being the key distinguishing features (Table II).

Table II Classes of Radioactive waste and potential disposal options (Modified from [11])

Waste classes	**Properties**	**Disposal options**
1. Exempt waste (EW)	Activity below clearance levels. Based on annual dose to members of critical group less than 10 μSv	No restrictions
2. Low and intermediate level waste (LILW)	Activity higher than class 1. Low thermal power	
2.1. Short-lived	Content of long-lived radionuclides restricted by regulatory authority on the basis of safety considerations.	Near surface or geological disposal
2.2. 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 LILW)
3. 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

Near surface repositories, where the disposal units are within tens of metres of the surface, provide adequate containment for short-lived LILW and for some long-lived LILW where greater confinement is required. Institutional controls provide assurance of adequate performance of the waste isolation barriers during the period of their anticipated duration. The rationale for near surface disposal depends on the assumption that by the end of the institutional controls period the activity of the waste will have decayed to harmless levels, as shown by adequate 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 LILW and for high level waste. The depth required for geological disposal depends on the geology of a specific site and the amount and type of waste for disposal.

DISPOSAL OPTIONS FOR DISUSED RADIOACTIVE SOURCES

Disused radioactive sources are, in principle, classified under the disposal categories listed in Table II as either short- or long-lived LILW. However, for many repository operators, radioactive sources are a special case because of their high specific activity, as discussed above. The suitability of a disposal option depends on the activity of the source and the waste acceptance criteria for a particular facility. An important component in the safety assessment for a near surface repository is estimation of the dose from inadvertent intrusion scenarios, which are very sensitive to the specific activity of the waste in the repository at the time of intrusion. Radioactive sources in a disposal facility can represent "hot spots" because of very concentrated radioactivity contained in a small volume.

Radioactive sources cover a very wide range of activities. These can be classified into weak (<10 GBq), medium (10 GBq to 10 TBq) and strong (>10 TBq) [1]. Sources of particular concern for disposal are high-activity sources containing ^{60}Co, ^{90}Sr and ^{137}Cs, and 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 source half-life.

Higher-activity (strong) sources and longer-lived sources obviously require a greater degree of containment. This is illustrated schematically in Fig. 2, representing source strength plotted against source half-life.

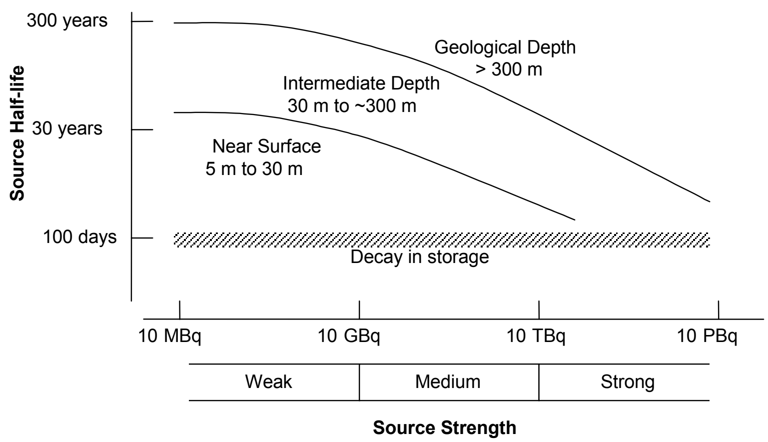

Fig. 2 Potential options for disposal of radioactive sources

Even countries that have no other nuclear activities must still safely manage inventories of radioactive sources. Some of these countries have very limited nuclear facilities and there is an urgent need to ensure long term control of disused radioactive sources.

A range of technical solutions is available for the disposal of radioactive waste, including radioactive sources, and their choice depends on many factors, such as the category of waste, national polices and strategies, waste acceptance criteria, safety assessment results, *etc*. Authorities in a Member State may consider a range of disposal options. For example, countries with active nuclear programmes, such as Finland, France, Japan, Spain, United Kingdom, and others, may chose to dispose of some of their Category 1 and 2 sources in currently-operating near surface repositories, while for higher-activity Category 2 and most Category 3 sources a greater-confinement repository would be required.

The potential disposal options for radioactive sources are presented in Table III [12]. In general, Category 1 sources (half-life < 100 days) can be kept in storage to allow them to decay to exemption levels. Alternatively, Category 1 sources are suitable for all types of controlled disposal because they will decay to very low levels within even short duration institutional controls periods.

Table III Potential disposal options for radioactive sources

Disposal Option	Type of Sources
Storage until decay, then disposal as exempt wastes (*e.g.* to landfill)	All Category 1 sources
Simple near surface facility with no engineered barriers (trench-type facilities)	All Category 1 and weak Category 2 sources
Engineered near surface facilities (e.g concrete vaults)	Weak Category 2 and 3 sources
Intermediate-depth shaft or borehole facilities with no engineered barriers	Medium Category 2 sources and weak Category 3 sources
Intermediate-depth shaft or borehole facilities with engineered barriers	Medium Category 2 and 3 sources
Intermediate-depth mined repository (*e.g.* LLW-ILW caverns)	All Category 2 sources and medium Category 3 sources
Deep boreholes at depths associated with geological disposal, with or without engineered barriers	All Category 2 and 3 sources
Geological repository	All Category 2 and 3 sources
Source strength: weak sources: < 10 GBq medium sources: 10 GBq to 10 TBq strong sources: > 10TBq	Depths: near surface disposal: < 30 m depth intermediate-depth disposal: 30 m to ~300 m deep boreholes: > ~300 m geological repository: > ~300 m

DECIDING ON A DISPOSAL OPTION

As discussed in the previous Section, there is a range of potential options available for the disposal of radioactive sources. This Section introduces a simple and straightforward approach for deciding which disposal option could be the most appropriate solution for a given source inventory.

Figure 3 shows the disposal options schematically, with shallow facilities being generally located at less than about 30 m depth, deep facilities being at depths greater than about 300 m (depths generally associated with geological repositories) and intermediate depth facilities in the range from about 30 to around 300 m below the surface.

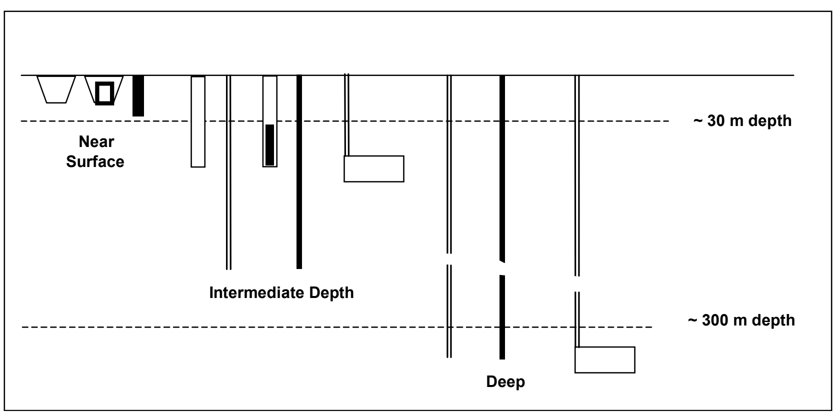

Fig. 3 Schematic representation of conceptual options Suitable for the Disposal of Disused Radioactive Sources.

Category 1 sources

For all category 1 sources, disposal simply means safe and secure storage pending decay, followed by disposal as exempt commercial or industrial wastes, according to national regulations and practices. Storage might be at centralized or dispersed facilities. Category 1 sources could also be disposed of in existing near surface, intermediate depth or geological repositories.

The lowest activity radioactive wastes or exempt waste are often acceptable for disposal in landfill sites used for domestic and industrial wastes. National regulations set activity concentration levels for such practices. Certain types of sources, including some with very low concentrations of long-lived radionuclides (*e.g.* smoke detectors) can be disposed of in a dispersed fashion in landfills as exempt waste. Bulk disposal of such sources in packages is not acceptable, as activity concentration limits may be exceeded.

Smaller scale, near surface facilities (typically concrete- and steel-lined boreholes and pits of a few cubic metres capacity or less) are used for storage of radioactive sources in some countries (*e.g.* Radon-type facilities) [13]. For Category 1 and lower-activity Category 2 sources, these types of facilities can be subject to a period of institutional controls that is sufficient for them to be used for disposal. For higher-activity Category 2 and 3 sources, they can only be considered as storage facilities and the wastes would need eventually to be retrieved for disposal in a deeper facility. This type of storage serves the function of providing safe and secure immediate containment and, for relatively short half-life Category 2 sources, it allows some activity decay prior to disposal.

Category 2 sources

For most category 2 sources (except higher-activity), disposal is required in licensed waste repositories. Existing near surface disposal facilities used for nuclear fuel cycle wastes are appropriate for the disposal of these sources, although the type of sources needs to be matched closely to the design of the repository and, as discussed above, this would generally only be available for disposal of radioactive sources in countries with existing LILW disposal facilities. As mentioned above, this option is only suitable for Category 1 sources and lower-activity Category 2 sources, which will have decayed to innocuous levels during the institutional controls period. Some sources cannot be disposed of in near surface repositories, owing to the continued risk posed by high specific activity sources after the institutional controls period, when there is a possibility of inadvertent human intrusion. Countries that have active handling facilities available might consider dismantling some very high-activity sources and dispersing the activity in a waste conditioning matrix so that it can be disposed of in a near surface repository, where it would decay without ever posing a risk as a concentrated 'hot-spot'.

In this paper, we assume that all near surface disposal facilities are subject to a period of institutional controls, assumed in many Member States to be about 300 years. Extended institutional controls (*e.g.* to 500 years) could provide significant additional decay time for high-activity Category 2 sources, but it is not recommended as a solution as it imposes an undue burden on future generations that runs against presently accepted principles of radioactive waste management. In many countries, no realistic institutional controls period can be relied upon. As discussed earlier, the anticipated institutional controls period is thus a very sensitive parameter in decisions concerning disposal of Category 2 sources. For Category 3 sources, their half-lives are too long for institutional controls to be of any relevance.

For the near surface disposal option, a performance assessment is also required to determine whether 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 facilities used for disposal would be existing licensed facilities, this analysis would be based upon that used for the full repository.

If no repositories are available or likely to become available in the near future, then provision can be made for disposal of radioactive sources in purpose-designed facilities, designed to accommodate the generally small volume of radioactive sources. The concepts that are discussed here involve pits, boreholes and shafts, constructed to varying depths and with varying levels of engineered containment, matched to the characteristics of the radioactive sources they are to hold [12, 14].

Category 3 sources

Category 3 sources and higher-activity Category 2 sources, not acceptable for disposal in near surface disposal facilities because they will not decay sufficiently within the period of institutional controls, 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, so disposal carried out 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 at intermediate depths are small.

Shafts, pits or boreholes to depths of several tens of metres or more are relatively simple to construct and may offer an attractive disposal option. If the safety assessment shows that adequate safety can be achieved without the emplacement of engineered barriers, additional to those contained in the disposal packages, then it appears logical that such emplacement methodology would be chosen. It is anticipated that such relatively favourable situation might occur in conditions of limited or no contact between percolating water and the radionuclides contained in the disposal packages.

The borehole disposal option is particularly attractive in the sense that it has a number of potentially favourable characteristics both from a technological and safety point of view. 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 variable depth and small footprint, a borehole-type facility has the potential to safely dispose of all types of radioactive sources, ranging from high-activity sources, which emit heat and intense radiation, to sources that contain long-lived radionuclides, such as ^{226}Ra and ^{241}Am. A borehole disposal facility may consist of a single borehole or a series of boreholes of varying depths, depending on the source inventory and characteristics. Given the limited land area requirements, a borehole facility, specifically designed for the disposal of radioactive sources, also has the potential to be co-located with existing nuclear facilities in a given Member State.

Shafts or boreholes excavated in arid environments in the unsaturated zone can offer adequate containment in the absence of any additional engineered barriers. Examples of such disposal units are the shafts at the Greater Confinement Facility, Nevada Test Site [15], and at the Australian facility at Mt. Walton East [16]. 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 categories 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 that reconstitute the original properties of the rock formations penetrated is recommended for all or some 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.

The engineered barrier system may consist of various components shown schematically in Fig. 4 (for boreholes and shafts). Table IV indicates the typical containment functions of engineered barriers in boreholes and shafts.

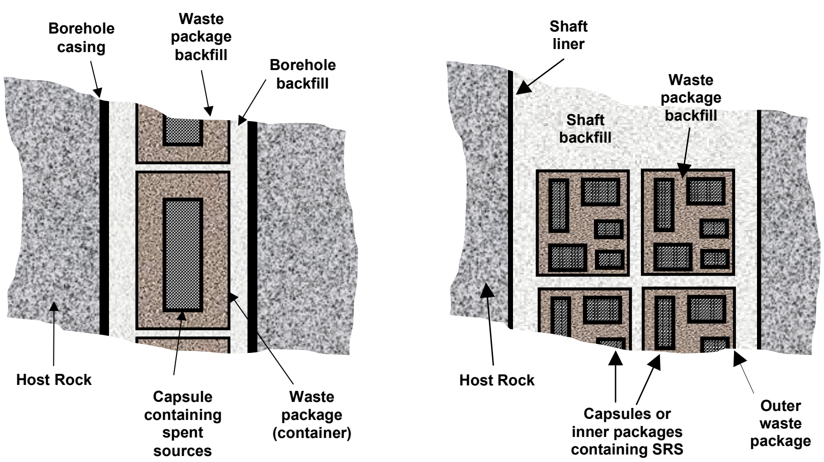

Fig. 4 Schematic illustration of possible engineered barrier components in a borehole (left) or shaft (right) disposal facility

Table IV Typical components of an engineered barrier system and their possible functions

Component	**Possible containment function**
Original source container	Conservatively, assume none (some sources may be damaged).
Welded metal (e.g. stainless steel) **capsules** for very small sources (e.g. radium needles)	Containment of activity until failure by corrosion in contact with pore-waters 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 by corrosion in contact with pore-waters in borehole/shaft backfill.
Container 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 containers (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 limited containment function.
Seal: long (several m) clay or cement plugs placed above the disposal zone	Seal waste disposal zone from shallower regions of disposal system and prevent vertical, short-circuit release pathways.

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

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

Currently, an IAEA-sponsored, regional technical assistance project in South Africa is carrying out an assessment of the technical feasibility and economic viability of the borehole concept for the disposal of disused radioactive sources in African countries [17]. Organized by the IAEA, an International Peer Review of the South African borehole disposal concept is planned to be held in Pretoria, South Africa in 2004.

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 hold short-lived LILW. The containment provided by such repositories often comprises massive concrete vaults or silos, with additional engineered barriers such as clay backfills and buffers. This type of containment would be adequate for the disposal of many, if not all types of sources, so that countries having access to a national or regional repository could consider storing 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, or regulatory constraints related to maximum activity concentrations).

Emplacement of high-activity sources in a mined, intermediate-depth repository would need to consider appropriate packaging and activity concentrations that are limited to match the thermal characteristics of the host rock and engineered barrier systems of the repository.

The objective of using deeper boreholes would be to remove relatively limited volumes of radioactive waste, including radioactive sources, to 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 engineered barriers beyond those needed to emplace the sources into the borehole and to maintain borehole stability during emplacement operations (casing and cementing).

This option is particularly suited for the higher-activity Category 2 and longer-lived Category 3 sources, where a long containment period is required (*e.g.* ~10 - 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, resulting in exposures to high concentrations of radionuclides before the sources have decayed.

Evaluation of this option would need to consider the mechanical and thermal loads that could result from source emplacement. Packages need to be sufficiently robust that they can resist the load of a column of packages for the duration of operations until the boreholes are sealed. The total thermal load within a borehole needs to be controlled by adapting the emplacement density of high-activity sources. The objective is to prevent damage to the borehole lining during operations and the possibility of thermal convection in borehole fluids both during operation and post-closure.

Emplacement of high-activity sources in a geological repository would need to consider appropriate packaging and activity concentrations that are limited to match the thermal characteristics of the host rock and engineered barriers of the repository.

CONCLUSION

The high specific activity and the long half-life of some of the isotopes in radioactive sources cause problems in fitting some disused sources into the waste disposal schemes of many countries. Their high activity and extremely small volume mean that many will not fit in the category of short-lived or low-activity LILW that are acceptable for disposal in near surface repositories with shallow disposal units. This is because the commonly accepted duration of the institutional controls period may not be sufficient to allow the sources to decay to harmless levels. One of the alternative routes, geological disposal, is not yet available, and is unlikely ever to become available in countries that have no nuclear power programmes requiring such solutions. As a result of this situation, most disused radioactive sources are currently kept in storage; a situation that, as shown by a number of incidents, can represent a high risk.

This report has discussed the full range of disposal options that might be used for all types of disused radioactive sources, with special attention being paid to the technological features of the different options. It provides a simple scheme to help the owners of radioactive sources decide what would be the most appropriate disposal option for different types of sources, based upon their half-lives and their strengths.

Intermediate-depth or deep geological repositories may eventually become available options for some countries, but this report has not discussed the source packaging and management requirements for such disposal, as these would be integrated into well-developed national plans. The focus is instead upon options for those countries that will not have access to such facilities and which must consequently develop their own, or shared, multi-national solutions. Due to the relatively small volume of radioactive sources, disposal units characterized by small dimensions, such as boreholes and shafts have been discussed in particular detail. Such disposal options have, to date, received much less attention then other types of disposal facilities in IAEA documents.

It is obvious that any kind of disposal option for radioactive sources, in order to be authorized by the appropriate regulatory authorities, needs to satisfy the relevant safety requirements. Shafts and boreholes can be excavated or drilled to different depths depending on a variety of factors, such as the level of isolation required by radioactive sources, the local stratigraphy and the hydrogeological conditions.

The safety objectives for disposal of small volumes of radioactive waste in shafts and boreholes can be met by various combinations of isolation barriers. Whenever the natural barriers are estimated to provide adequate containment, it is conceivable that the containers/packages containing the source capsules, could be relatively simple and inexpensive. While for disposal units characterized by less reliable natural barriers, durable waste packages and additional engineered barriers could be used.

Disposal of radioactive sources in shafts or boreholes, apart from satisfying safety requirements and being attractive from an economic viewpoint, is considerably more flexible and modular, has no large initial investment demands and is less intrusive on the landscape than conventional disposal facilities. Since it also has similar or even better containment performance than other disposal options, the disposal in shallow- and intermediate-depth boreholes has been practised or proposed for different types of radioactive waste in various countries and presently is being assessed internationally.

The depth of disposal boreholes could vary greatly, depending on a variety of specific factors, such as the characteristics of the sources (activity and longevity of radionuclides, etc.), technical features of the engineered barriers (corrosion resistance of package materials, nature of backfill, etc.) and properties of surrounding geological medium (hydrogeological and geochemical characteristics). It is anticipated that in most cases borehole depths in the order of tens of metres could be adequate, but there is no conceptual reason to prevent the use of boreholes reaching depths of hundreds of metres, that is, in the depth range typical of geological repositories.

The broadly available drilling technologies provide adequate technical tools for the implementation of the borehole disposal concept. For the purpose of disposing of sources, 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 the 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. While depth provides inaccessibility from intrusion and protects the radioactive sources from infiltration of rainwater, and from climatic and other dynamic, near surface phenomena, design features of both source packages and 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 to inadvertent intrusion.

The engineered barrier system in any disposal concept may consist of various components, including casing, containers/packages, buffer mass, backfill, any chemical additives or liners, plugs and caps. Depending on the containment period required, some or all of these components may be included in the safety concept design, each with its own purpose.

Natural barriers, particularly for the disposal of long-lived radioactive sources, are expected to play an important role in assuring the performance of the overall disposal system. In assessing the performance of natural barriers (physical and chemical properties of the host rocks, hydrogeology and groundwater chemistry), it is important to consider how they control the interaction processes in the near field and how they respond to the construction of the disposal units and the presence of engineered structures.

An example of a favourable situation for hosting disposal units for radioactive sources would be an unsaturated sandy host rock in an arid location. Due to the absence of significant quantities of moving groundwater, disposal in the unsaturated zone may be superior to alternative options involving the emplacement of radioactive sources below the water table. Other favourable disposal conditions can be found in low-permeability rocks that, even if in the saturated zone, experience low groundwater flow, in particular clay-rich, host rocks.

Eventually, providing an adequate level of assurance to decision makers and the general public that a particular disposal concept for radioactive sources is capable of meeting the relevant safety objectives both at present and in the future can be achieved by presenting a convincing safety case. Some generic safety assessments have been performed, regarding the disposal of sources in boreholes. The positive results of the assessments indicate that disposal in boreholes and shafts can be considered as a viable option for the disposal of radioactive sources and can offer significant advantages in respect to more conventional near surface and intermediate-depth disposal options.

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