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Safety considerations in the disposal of disused sealed radioactive sources in borehole facilities

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SAFETY CONSIDERATIONS IN THE DISPOSAL OF DISUSED SEALED RADIOACTIVE SOURCES
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FOREWORD

Sealed radioactive sources are used in medicine, industry and research for a wide range of purposes. They can contain different radionuclides in greatly varying amounts. At the end of their useful lives, they are termed ‘disused sources’ but their activity levels can still be quite high. They are, for all practical purposes, another type of radioactive waste that needs to be disposed of safely.

Disused sealed radioactive sources can represent a significant hazard to people if not managed properly. Many countries have no special facilities for the management or disposal of radioactive waste, as they have no nuclear power programmes requiring such facilities. Even in countries with developed nuclear programmes, disused sealed sources present problems as they often fall outside the common categories of radioactive waste for which disposal options have been identified. As a result, many disused sealed sources are kept in storage. Depending on the nature of the storage arrangements, this situation may represent a high potential risk to workers and to the public.

The International Atomic Energy Agency (IAEA) has received numerous requests for assistance from Member States faced with the problem of safely managing disused sealed sources. The requests have related to both technical and safety aspects. Particularly urgent requests have involved emergency situations arising from unsafe storage conditions and lost sources. There is therefore an important requirement for the development of safe and cost-effective final disposal solutions. Consequently, a number of activities have been initiated by the IAEA to assist Member States in the management of disused sealed sources.

This report discusses the general considerations related to the safe disposal of disused sealed sources, and other limited quantities of radioactive waste, in boreholes facilities. It is particularly aimed at Member States who do not plan to develop other types of disposal facility for nuclear fuel cycle waste.

It is recognized that internationally agreed safety guidance is needed in this area but further development and consultation is required to establish broad international consensus on the appropriate technology and safety requirements.

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1. INTRODUCTION

1.1. BACKGROUND

Radioactive sources have been in use since 1901, and up until about 1940, the main application was the use of radium sources in medicine. Since then, there has been a considerable increase in the number and diversity of sealed sources, and the range of radionuclides that they contain. Today, radioactive sources are widely used in medicine, research, industry, agriculture and in a number of consumer products. The majority of sources are small in physical size, with the only items of significant size being some industrial radiography units and commercial irradiators. The radionuclides incorporated into sealed sources depend on their intended use. For example, sealed sources used as irradiators usually contain ^{60}Co or ^{137}Cs, power sources contain ^{238}Pu and neutron sources contain ^{241}Am. In the past, ^{226}Ra was extensively used in sources for medical applications, resulting in the widespread storage of radium needles around the world. An overview of management practices for disused sealed sources, including their handling, conditioning and storage, is given in Annex A.

Despite their predominantly small physical size, many sources contain very high concentrations of radionuclides. Industrial and medical sources are typically in the GBq to PBq range. The radiation emitted from these sources is usually intense, requiring heavily shielded containers for their safe use, transport and storage. If not properly managed such sources can give rise to very serious safety problems, particularly when items of industrial or medical equipment containing sources become obsolete and are replaced, or simply scrapped. Poor management practices in many parts of the world have resulted in disused sources having been found stored in unsatisfactory conditions. Often the sources themselves are in a poor condition, and in some cases radioactive material has leaked from inside the usually metal encapsulation. There have been a number of recorded incidents [3] involving fatalities in the last forty years that have arisen due to control over disused sources being lost and the sources being inadvertently mishandled by members of the public. In fact the use of these types of radioactive materials is one of the largest single contributors to accidents associated with peaceful applications of radiation related technologies [1].

Clearly, disused sources need to be managed and disposed of carefully and in a safe manner. Some sources can be returned to their manufacturers and recycled, but for many users of sealed sources it is impractical or uneconomical to recycle all sources, and a large number of sources end up being stored for long periods of time. Storage can be considered as an adequate final management option for sources containing only short lived radionuclides, which decay to harmless levels in a few years. However, most other sources remain in storage pending a suitable disposal option becoming available.

Many countries with nuclear power programmes have developed near-surface radioactive waste disposal facilities for low and intermediate level waste. However, the specific activity of many sources exceeds the waste acceptance criteria for such facilities. In the relatively small number of cases where disused sources have been disposed of in dedicated facilities, reasonable assurance of compliance with the relevant safety requirements has not always been adequately demonstrated. The problem in this respect is that they constitute high, localised concentrations in the facility and could give rise to unacceptable radiation doses in the event of human intrusion. Safety cases for many disposal facilities assume a period of institutional control (typically a few tens to hundreds of years) during which human intrusion is assumed to be unlikely. However, even within these and particularly for longer time frames it is possible that such control will no longer be fully in place and thus human intrusion cannot be ruled out.

Consequently, radioactive sources that will not decay to negligible levels within a few hundred years need to be disposed of in facilities that will provide higher levels of isolation than provided by surface storage or near-surface repositories. Deep geological disposal offers the highest level of isolation available within disposal concepts currently actively considered. Such facilities are under consideration for the disposal of spent nuclear fuel, high level waste and intermediate level waste in a number of countries. However, they are extremely expensive to develop. It is unlikely that such an option will become available in the foreseeable future in many countries. The safe long term management of disused radioactive sources thus remains an open question.

Moreover, many countries lack an infrastructure for the long term management of radioactive waste, as they have no nuclear power programme requiring such resources. The borehole disposal concept could possibly provide a solution for the long term management of disused sealed sources in these countries, and they are the primary intended audience for this report.

There is presently no international mechanism for the collection and long term management of disused sources, although the IAEA does provide assistance in rendering sources into a safe state by conditioning and encapsulation. In view of these circumstances, a disposal system that could be developed and operated in a country or region at a reasonable cost and provide a good level of safety for human health and the environment would be a desirable option. Disposal in borehole facilities could have the potential to meet these requirements.

The impetus for developing the present document arises from a number of questions that have been raised at an international level about whether the borehole disposal concept and particular borehole disposal systems are fully consistent with the fundamental principles of radioactive waste management [4]. For example, concerns have been expressed over the degree of isolation provided by certain borehole facilities in terms of depth of the boreholes, reliability and efficiency of the isolation barriers and the adequacy of the associated safety assessments.

It is recognized that boreholes are straightforward to drill but the safety aspects of borehole disposal are not necessarily straightforward. However, it should be stressed that the time, resources and data for borehole safety assessments need to be commensurate with the potential hazard. In particular, they are likely to be significantly less than for near-surface or geological repositories. Moreover, the IAEA is in the process of carrying out generic assessments for borehole facilities, as discussed in this report, which it is anticipated will facilitate the site-specific assessment of proposed borehole facilities.

1.2. OBJECTIVES

The objective of this report is to address safety issues relevant to the disposal of disused sealed sources, and other limited amounts of radioactive waste, in borehole facilities. It is the first in a series of reports aiming to provide an indication of the present issues related to the use of borehole disposal facilities to safely disposal of disused sealed radioactive sources and other smaller quantities of radioactive waste and to identify areas were further work needs to be undertaken.

2. BOREHOLE DISPOSAL AS A RADIOACTIVE WASTE MANAGEMENT OPTION

All radioactive sources, which cannot be cleared from regulatory control, need to be collected, stored and safely managed in the long term. Most of them will eventually need to be disposed of safely in an appropriate facility. However, a considerable number of higher activity sources exceed the specific activity limits for waste to be accepted in near-surface disposal facilities, and geological repositories are not generally available. In these circumstances, the borehole disposal option is a potential solution for a number of Member States.

2.1. BOREHOLE DISPOSAL CONCEPT

The borehole disposal concept entails the emplacement of solid or solidified radioactive waste in an engineered facility of relatively narrow diameter bored and operated directly from the surface. Borehole disposal facilities cover a range of design concepts with depths ranging from a few metres up to several hundred metres. Their diameters can vary from a few tens of centimetres up to more than one metre [5–7]. The borehole may have a casing and the waste would normally be contained within an engineered package that is surrounded by backfill material. In some facilities of the "Radon" type design, disused sealed sources have been disposed of without additional packaging. A disposal facility may consist of a single borehole or a group of boreholes that may or may not be located in conjunction with other nuclear facilities. The underlying common characteristic of all borehole facilities is their small physical size (footprint) at the surface, which reduces the likelihood of human intrusion into such a facility. Also, the limited radionuclide inventory intrinsically limits the potential hazards to people and the environment.

Borehole disposal facilities have a number of potentially favourable characteristics of potential benefit from a waste safety and economic point of view namely they:

- Provide long term isolation from humans and the environment for small volumes of high specific activity radioactive waste in high integrity waste packages;
- Provide direct and cost effective access to a suitable geological horizon, using readily available technology. In particular, an appropriate depth of disposal and geological horizon can be selected in a cost-effective manner;
- Require limited land area and limited infrastructure;
- Require short periods of construction, operation and closure;
- Can be developed as and when required to dispose of waste as it arises;
- Have a low probability of human intrusion and future disruptive events due to the small footprint of the borehole and the ability to select a suitable depth;
- Require minimal post-closure control over the disposal site.

Thus the borehole concept could potentially provide a cost effective and safe disposal option, particularly for countries with limited nuclear infrastructure.

Once a borehole has been sealed, retrieval of the waste would be difficult. However, retrieval would be relatively straightforward during any post-emplacement pre-closure phase when the facility would be under institutional control and monitored.

Borehole facilities have been used in the past in a number of countries for storage and disposal of radioactive waste. These are all located on existing waste repository sites. A brief review of these facilities is presented in Annex B.

Borehole disposal facilities are presently being planned, for example in Russia [5], often as an extension of an existing disposal facility. Also, the AFRA programme co-ordinated by the IAEA is currently developing this concept design for use in African countries [6, 7]. Borehole disposal facilities hold out particular promise for countries, or regional groupings of countries, that only have a small number of disused sources.

From a safety perspective, borehole disposal is not conceptually different from either near-surface or geological disposal of radioactive waste. It aims to achieve safety by a combination of natural and engineered barriers together with institutional control at early times. In combination, these safety functions are designed to contain the activity until it has decayed to insignificant levels, and to provide sufficient isolation and containment to ensure an adequate level of protection for humans and the environment.

Borehole disposal is not just a means of enhancing the safety of disused radioactive sources. It also enhances their security by making it difficult for terrorists to gain access to radioactive materials following emplacement in a borehole for either storage or disposal.

2.2. TECHNICAL FACTORS

The most appropriate and acceptable long term management or disposal option depends primarily on the time for the radionuclides in the waste to decay to an insignificant activity level as well as on the physical and chemical form of the waste. This in turn depends on the initial activities and half-lives of the radionuclides. The characteristics of a range of sealed sources are tabulated in Annex A.

Sources containing radionuclides with half-lives of less than a few hundred days (Category 1 in Table A-2 of Annex A), can generally be stored while they decay to negligible levels over ten or more years after which they can be removed from regulatory control and do not need to be disposed of as radioactive waste [8, 9].

The next important group of radionuclides have half-lives in the range between 100 days and about thirty years (Category 2 in Table A-2 of Annex A). If the activities of these sources are such that they decay to insignificant levels from a radiological safety perspective during the period of institutional control, then they can be considered for near-surface disposal at depths of metres to a few tens of metres. This could be in a near-surface disposal facility, if they comply with the waste acceptance criteria for the facility approved by the regulatory authority. Alternatively, disposal in near-surface boreholes may be suitable for a limited number of sources, although the adequacy and safety of this disposal option for specific inventories needs to be assessed on a case-by-case basis. A key factor in deciding whether sources are suitable for either type of near-surface disposal is the timescale assumed for effective institutional control. This may depend on whether the site will be controlled for other purposes, for example to maintain security at a nuclear facility, and also on the regulatory position. Typical periods assumed for institution control range from a few tens of years to a few hundreds of years.

If the activities of sources containing Category 2 radionuclides are such that they do not decay to insignificant levels within the institutional control period, then they would generally need to be considered along with Category 3 radionuclides as discussed below.

The final group of radionuclides have half-lives in excess of about thirty years (Category 3 in Table A-2 of Annex A). In most cases such sources are not acceptable for disposal in near-surface repositories. Such sources need to be disposed of in facilities that are able to provide protection and isolation from the environment for thousands of years. For example, they could be disposed of in a geological disposal facility if such a facility becomes available. Alternatively, borehole disposal at sufficient depth in a suitable geological environment could be considered.

A programme for selecting and characterizing a site, and for, design, construction, operation, closure and post-closure activities needs to be developed and implemented, as outlined in Annex C. This needs to include a safety assessment of the long term performance of the borehole disposal system. The extent of these activities needs to be commensurate with the potential hazard posed by the proposed inventory to be disposed.

Key factors that need to be considered with regard to the long term safety of borehole disposal are the waste inventory, extent of containment and isolation needed, depth of waste emplacement, the characteristics of the engineered and natural barriers, likelihood of human intrusion, and the length of the assumed institutional control period. This report attempts to identify robust approaches for achieving an acceptable level of long term safety for borehole disposal facilities. In this regard IAEA activities addressing the design of borehole facilities [6] and safety assessment methodologies [10, 11] have been considered and provide a generic basis for further adaptation to site-specific conditions. The following sections of this report discuss these matters in detail.

2.3. OTHER FACTORS

Development of a radioactive waste disposal facility such as a borehole in practice not only requires a demonstration of compliance with safety and technical requirements but at the same time consideration of a number of non-technical factors, such as the involvement of stakeholders (e.g. public, non-governmental organizations) and the balancing of costs and benefits. Public participation in environmental impact assessment processes and related decision-making is required in many countries. Moreover, a comparison between options, one of which could be to leave the waste, including disused sealed sources in extended storage. Such comparisons can serve to emphasize the safety and security benefits of isolating these radioactive materials from the immediate environment. The range of stakeholder concerns generally extends beyond regulatory requirements. In particular, the perception of risk that is of relevance to societal concerns is much broader than the quantitative definition of risk used within radiation safety. For example, it encompasses factors such as trust in institutions, equity, benefits and reversibility [12]. In response to this, there is an increased emphasis on openness and transparency by radioactive waste organizations, and new approaches are being used to engage the broader range of interested and affected parties in dialogue [13, 14].

A common feature of radioactive waste disposal programmes is that they encounter difficulties in gaining acceptance from local communities and other non-institutional stakeholders. From the perspective of wider groups of stakeholders, confidence is enhanced by the knowledge that radioactive waste disposal has an environmental and ethical basis [15] and is built on a set of internationally agreed fundamental principles [4]. It can be anticipated that other factors such as involvement of different stakeholders will play a role in the development of borehole disposal facilities. However, because of the clear medical and industrial benefits arising from the use of sealed sources, public acceptability may be less of an issue than for wastes from nuclear power stations for which there is not a universal consensus as to the benefits. Nevertheless in developing, structuring and presenting arguments about the safety of borehole facilities and their potential benefits in removing spent sources from the accessible public domain, careful consideration must be given to the potential audiences. The arguments must be structured in a manner that is clear and which can be understood by non-technical persons.

3. SAFETY REQUIREMENTS

A fundamental requirement for all disposal practices is that they should comply with the IAEA principles of radioactive waste management as set out in Box 1 [4].

Disposing of disused sealed sources, and other small quantities of waste, in boreholes is a variation of current practices for near-surface or deep geological disposal of much larger volumes of radioactive waste from nuclear facilities. In particular the safety requirements for borehole disposal facilities are related to those for near-surface [16] and geological repositories [17, 18]. As with other waste disposal options, there is a requirement for multiple safety functions including engineered and natural barriers that work together to provide the required degree of containment and isolation. In addition there is a requirement for iterative design and safety assessment, and the application of a high level of quality management practice in the whole process.

However, the level of effort required to comply with these requirements for a facility with a single or limited number of boreholes should be significantly less than for near-surface or geological repositories in terms of the facility construction, operation and closure. This is mainly due to the small volume and limited inventory of the waste. Because of these factors the borehole concept has been considered as a straightforward disposal option.

The assessment and justification of borehole disposal safety needs to be adequately demonstrated with reasonable assurance to the regulatory authorities and other relevant stakeholders, and this is not necessarily a straightforward matter. Nevertheless, it is important to stress that the degree to which the safety requirements [16, 18] are applied needs to be commensurate with the hazard. Thus, in general, safety assessments for borehole disposal facilities will require less time, resources and data than for near-surface or geological disposal facilities. Moreover, in order to facilitate the safety assessment of borehole facilities, the IAEA is exploring the development of generic assessments and the way and extent to which they can assist in assessments for particular sites, as discussed in Section 5.2.3.

3.1. GENERAL REQUIREMENTS

Borehole disposal facilities should follow the relevant safety principles throughout the lifetime of the facility, namely during site selection and characterization, design, construction, operation, closure and post-closure. The generic safety requirements applicable to borehole disposal facilities (outlined in detail in Sections 4 and 5 of this publication) are:

- Compliance with radiological protection requirements for disposal practices, as contained in the IAEA safety standards. This will be judged primarily on the basis of estimates of individual radiation doses that could result from a disposal facility during its operation and following closure;

Box 1
Safety Fundamentals
The Principles of Radioactive Waste Management [4]

Principle 1: Protection of human health

Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health.

Principle 2: Protection of the environment

Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment.

Principle 3: Protection beyond national borders

Radioactive waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be taken into account.

Principle 4: Protection of future generations

Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today

Principle 5: Burdens on future generations

Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations.

Principle 6: National legal framework

Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.

Principle 7: Control of radioactive waste generation

Generation of radioactive waste shall be kept to the minimum practicable.

Principle 8: Radioactive waste generation and management interdependencies

Interdependencies among all Activities in radioactive waste generation and management shall be appropriately taken into account.

Principle 9: Safety of facilities

The safety of facilities for radioactive waste generation and management shall be appropriately assured during their lifetime.

- Provision of multiple safety functions including engineered and natural barriers and institutional control for an initial period;
- Use of good engineering practice for all phases of design and development;
- Minimization of the likelihood and consequences of natural and human disruptive events by appropriate siting and design so as to limit to the extent possible the necessity for continued supervision, surveillance or management of the disposal site once it has been closed;
- Provision of adequate control over the design, construction, operation and closure activities of the borehole facility, and specifically over compliance with the waste acceptance criteria;
- Maintenance of information on the facility and its inventory so that it can be made available to future generations to enable them to make any appropriate decisions about the safety of the facility.

In addition there may be a need to consider the question of reversibility of stages in the facility development including waste retrievability, if required by a regulator or thought desirable by other relevant stakeholders [17, 19]. Borehole disposal is intended to be a permanent solution providing passive safety into the future. However, it would be possible to retrieve waste from a sealed borehole if required, for example by over-coring, but this would be a difficult and expensive procedure especially at increasing depth. Alternatively any concerns about retrievability could be addressed by initially storing the waste in the borehole in such a way that it could be easily retrieved. The facility could then be readily monitored with final backfilling and sealing taking place when there is confidence that it is performing as expected.

Borehole facilities need to be designed and implemented such that human health and the environment are protected from radiological hazards both now and in the future. The International Commission on Radiological Protection (ICRP) has developed a system of radiological protection that applies to all sources of radiation exposure, which has been adopted in the IAEA Basic Safety Standards [8]. The ICRP has elaborated the application of this system to the disposal of solid radioactive waste in ICRP Publications 77 [20] and 81 [18], and these provides the starting point for Sections 3.2 and 3.3 on radiological protection during the operational period and in the long term. Wider environmental and non-radiological concerns are discussed in Section 3.4.

3.2. SAFETY DURING THE OPERATIONS

During the operational phase of a disposal facility, safety can be assured by conventional operational radiation protection programmes, which are in accordance with relevant international guidance. In radiation protection terms, the source is under control and impacts can be verified. The objectives and criteria for safety during the operational period, required by the Basic Safety Standards [8] are set out below.

3.2.1. Objectives

The safety objectives during the operational period are that:

- *"Doses to workers and members of the public exposed as a result of operations at the disposal site shall be as low as reasonably achievable (ALARA), social and economic factors being taken into account"; and*
- *"Exposures of individuals shall be kept within applicable dose limits and constraints".*

The optimization of protection for workers needs to be considered in the disposal facility design and the planning of operations. Relevant considerations include the separation of drilling and waste emplacement activities, the use of remote handling and shielded equipment for waste emplacement, the control of working environments and emplacement conditions, minimization of the potential for accidents and their consequences and the minimization of maintenance requirements in radiation and contamination areas.

Only very minor releases of radioactivity are expected during the operation of a borehole facility. Gaseous releases of radionuclides may occur from some waste types and radionuclides might be released as a result of accidents. Relevant considerations should include the packaging, form and content of the waste, and control of contamination on packages and equipment.

3.2.2. Criteria

Internationally endorsed criteria for the protection of workers and of members of the public are contained in Schedules II and III of the Basic Safety Standards [8]. This specifies that, in general, "*occupational exposure shall be controlled so that the following limits for workers are not exceeded:*

- *"An effective dose of 20 mSv per year averaged over five consecutive years"; and*
- *"An effective dose of 50 mSv in any single year."*

The average dose to members of the public from all sources excluding background radiation should not exceed an effective dose of 1 mSv in a year[1]. To comply with this limit, *"the facility (which constitutes a single source of exposure) shall be designed so that the estimated average dose to the critical group of members of the public, who may be exposed as a result of the source,* does not exceed *a dose constraint set at an appropriate fraction of the dose limit. This dose constraint shall be not more than 0.3 mSv per year."*

3.3. SAFETY IN THE LONG TERM

The special concern and primary design goal in relation to borehole disposal is the protection of human health and the environment in the long term, after facility closure. In this period, the exposure of humans may occur due to:

- Migration of radionuclides to the environment due to degradation of barriers and other natural processes; and
- Human actions and other disruptive events in the future leading to a degradation of the borehole disposal system.

The ICRP has recommended a methodology and criteria for assessing these situations in its Publication 81 [18].

Constrained optimization is recommended as the central approach for natural evolution scenarios to provide for the radiological acceptability of a waste disposal system. This requires that *"the radiological detriment to members of the public shall be as low as reasonably achievable (ALARA), economic and social factors being accounted for"*. In this context, optimization of protection is a judgmental process with social and economic factors being taken into account and should be conducted in a structured, essentially qualitative way.

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[1] See Ref. [23] for specific circumstances and tissues.

The appropriate objectives and criteria for the protection of human health in the long term are set out below.

3.3.1. Objectives

The long term radiological protection objectives for a borehole facility are that:

- It should be sited, designed, developed, operated and closed so that protection in the long term is optimized, social and economic factors being taken into account; and
- As far as can be determined, the estimated doses or risks should be within applicable dose or risk limits and constraints.

An appropriate location for a borehole disposal facility is a geological environment that gives good prospects for the long term isolation of the waste and preservation of the engineered barriers. For example, favourable characteristics are sufficient distance from the ground water table, low groundwater flow and a benign geochemical environment at a site at which there is a low likelihood of natural events that could directly disturb the facility or its performance[2]. The disposal system needs to be designed to provide protection within the dose constraint for the natural evolution of the system. In this regard, the natural evolution takes account of the degradation of the engineered barriers over time and the expected evolution of the natural system including natural events over the period of assessment. Finally, the facility needs to be developed and constructed so that that assumed safety characteristics of the natural barriers are likely to be realized.

The borehole disposal facility needs to provide good prospects that radiological impacts in the long term will be low relative to any other long term waste management option that is currently available. Further optimization of a borehole facility design is a judgmental process applied to the decisions made during the development of the design. Protection is deemed to be optimized if:

- Due attention has been paid to the long term safety implications of the design options during its development;
- The assessed doses and risks for the normal evolution of the system fall below the relevant constraints;
- The probability of events that might give rise to doses above the constraint has been reasonably reduced by siting or design; and
- The design, construction, operational and closure programmes have been subjected to quality management.

3.3.2. Criteria

The currently applicable dose limit for members of the public is an effective dose of 1 mSv in a year [8], and this or its risk equivalent should be considered as a target not to be exceeded at times in the future[3]. To comply with this target, a borehole facility or such facilities on a

[2] This does not mean that a facility could not be located at a site estimated to have a significant likelihood of events leading to disturbance. However, the likelihood and impact of such events will need to be assessed and shown to be tolerable in comparison to the other advantages that the site may offer.

[3] The value cannot be considered as ‘limit’ since verification or assurance of compliance with the limit is not possible. However, it can be considered as a target that carries the same level of significance as the limit that applies in controlled circumstances.

disposal site (which constitutes a single source) needs to be designed so that the estimated average dose or risk to members of a potentially exposed group satisfies a dose or risk constraint. This constraint should be set at an appropriate fraction of the dose target or its risk equivalent. The appropriate fraction of the target would be determined in national policy or by the regulatory body but should not be greater than 0.3 mSv in a year. This corresponds to a risk constraint of the order of 10^{-5} per year.

In estimating the dose to individuals living in the future it is appropriate to assume that humans will be present, and that they will make some use of local resources that may contain radionuclides originating from the waste. One approach is to use actual habits and resource use of the present day local population as a model for future behaviour and resource use. Another is to consider more generalized hypothetical habits and resource use so as to derive a reasonable maximum for the calculated doses/risks. Whatever the approach, the doses calculated should be regarded as indicators of whether the facility is acceptable. The rationale and possible approaches to the estimation of doses as a result of solid waste disposal have been considered within the IAEA BIOMASS Project [11].

The possibility of elevated exposures from inadvertent human intrusion is an inescapable consequence of the decision to concentrate and contain the waste rather than dispersing it in the environment [18]. Protection from such exposures is best accomplished by efforts to reduce the possibility of such events, including disposal depth and reasonable measures to warn society of the existence of the disposal facility. The ICRP recommends that stylised human intrusion scenarios should be evaluated. If the indicative annual doses from such scenarios are above 100 mSv then reasonable efforts should be made to reduce the probability of human intrusion or to limit its consequences. However, if the calculated annual doses for stylised intrusion scenarios are below 10 mSv then such measures are not required. This does not apply to individuals that actually take part in activities that disturb the facility. A few individuals that take part in such activities may receive high doses, but this should be accepted as a consequence of the decision to concentrate and contain the waste, and is balanced by the generally high level of protection that the strategy offers.

It is recognized that radiation doses to individuals in the far future can only be estimated and that the reliability of these estimates will decrease at longer times into the future due to the higher level of the related uncertainties. In particular, it is not possible to estimate the future behaviour of humans. The ICRP has emphasized that doses and risks cannot be forecast with any certainty for periods beyond around 100 years into the future. However, estimates of doses and risks for longer time periods can be made and compared with the appropriate criteria in order to give an indication of whether the facility is acceptable given the current understanding of the disposal system. Such estimates should not be regarded as predictions of future health detriment.

The facility design process needs to be focused on ensuring that the waste disposal system offers an acceptable level of protection by assessing compliance with dose and risk constraints for the normal evolution of the system.

Some improbable or low frequency natural events have large uncertainties in their likelihood of occurrence and potential consequences. Thus compliance with dose or risk constraints cannot be assured. The primary means of protection from such events is to site the facility such that the likelihood of an event that could cause significant disruption is low. Beyond this, illustrative “what-if?” calculations may be performed for selected hypothetical events in order to understand the possible consequences and judge the importance of such events. In particular, it is appropriate to assess the resilience of the disposal system, and design measures may be considered to assure that if such an event occurs, it does not lead to a widespread decrease in safety.

In general, when uncertainties make the results of safety assessment calculations unreliable, comparison to constraints may not be appropriate or should be treated with caution. For a borehole facility, such circumstances are likely to apply when considering low frequency natural disruptive events.

3.4. ENVIRONMENTAL AND NON-RADIOLOGICAL CONCERNS

The assessment of conventional environmental impacts that may occur during the operational period, e.g. related to traffic, noise, visual amenity, disturbance of natural habitats, restrictions on land use and social and economic factors are outside the scope of this document. The focus here is on the protection of the environment from radioactive and possibly other contaminants, especially in the long term.

In the past it has been assumed that, subject to appropriate definition of exposed groups, protection of humans against the radiological hazards will also satisfy the need to protect the environment [18]. The need to consider the protection of the environment from ionizing radiation, and possible protection standards, is currently under discussion internationally, e.g. see [21], and developments are to be expected in this area.

It is already recognized that estimates of doses/risks due to future releases from a disposal facility are indicators of environmental protection. Additional indicators and comparisons, e.g. estimation of concentrations and fluxes of contaminants and comparison to naturally occurring concentrations and fluxes may also prove valuable to indicate an overall level of long term environmental protection that is independent of assumptions about human habits [22].

The impact of non-radioactive materials present in a borehole disposal facility will need to be assessed. Factors that need to be considered may include the content of chemically or biologically toxic materials in the waste or engineered barrier materials, the protection of groundwater resources, and the ecological sensitivity of the environment into which contaminants may be released. For example, in some designs, lead is used as a container backfill material and its potential migration has been assessed.

4. SAFETY STRATEGY

The safety strategy defines the approach to designing and developing a disposal facility and for providing a reasonable assurance of the safety.

Safety means meeting the protection objectives and criteria defined and discussed in Section 3 by designing and implementing a total borehole disposal system wherein the components work together to assure the required level of protection. This means that it is the performance and safety of the total system that needs to be assured, in addition to each component of the system having an appropriate level of integrity. The approach offers flexibility to the designer of a disposal system because the disposal facility layout and engineered barriers can be adapted to take advantage of the natural safety relevant characteristics of the host rock and to provide engineered barriers that are consistent with and complement these. The total system approach stresses the performance of the overall disposal system rather than individual components or barriers, thereby enhancing confidence in the overall performance both now and in long term.

Experience shows that besides the development of the necessary technical and operational capability, the safe management of radioactive waste relies on an appropriate legal structure and regulations. As with all aspects of borehole disposal, the extent of the legal and organizational framework needs to be commensurate with the potential hazard. The IAEA has provided advice on an appropriate governmental, legal and regulatory infrastructure [23, 24].

Interim guidelines on the development of a safety strategy are set out below under three headings: legal and organizational framework, safety approach, and safety functions.

4.1. LEGAL AND ORGANIZATIONAL FRAMEWORK

The development of a borehole disposal facility should be carried out in compliance with relevant national regulations. In particular consideration needs to be given to ensuring:

- Compliance with radiation protection criteria for occupationally exposed workers and members of the public in normal operation and accidents;
- Compliance with operational limits and conditions, with specific emphasis on waste acceptance criteria;
- Implementation of corrective actions in case deviations are detected;
- Performance of adequate control of the disposal site (e.g. monitoring).

It is appropriate to carry out the operational, closure and post-closure activities in accordance with written procedures and instructions to ensure that identified limits and conditions for operations are observed and are carefully and properly followed. This will ensure that appropriate attention is given to safety in each step of the facility development.

The responsibilities and capabilities of the organizations involved in the development, regulation and monitoring of a borehole facility need to be identified.

It is common practice in siting waste disposal facilities to avoid environmentally sensitive regions (e.g. national parks, areas containing threatened species) and to take close account of local, regional and national public opinion and preferences. A borehole disposal facility will be considerably less intrusive and disruptive than, for example, a near surface or a deep geological repository. Nevertheless, social and planning factors need to be given a high priority by those identifying sites, and it is appropriate to seek advice and input from key stakeholders, both nationally and locally.

4.1.2. Government responsibilities

The government should provide an appropriate national legal and organizational framework, including the clear allocation of responsibilities and provision for independent regulatory functions, within which the disposal facility could be developed, operated and closed [23].

4.1.3. Regulator responsibilities

The regulatory body needs to establish regulations for the disposal facility, which are appropriate to the scale and potential hazard of the proposed facility. In addition, it is appropriate for the regulatory body to provide guidance on the interpretation of the regulations, as necessary, and also on the procedure that an operator is expected to follow in terms of license applications.

4.2. REGULATORY FRAMEWORK

Borehole disposal is an option for long term management of small quantities of radioactive waste, including disused sealed sources, in compliance with the internationally accepted principles for radioactive waste management [4]. The regulation of this disposal practice needs to cover all aspects of the borehole development with emphasis on the specific features of this concept. In the following discussion it is assumed that an appropriate regulatory body already exists in the country concerned.

The regulatory efforts in the field of radiation protection and radioactive waste management need to be commensurate with the magnitude of the activities within a country. The regulatory body needs to be kept independent from the organization assigned with the task of disposal, to extent possible. In order to achieve these objectives, advice from regulators in other countries may be necessary as well as guidance from international bodies like the IAEA.

4.2.1. Regulatory process

Regulation of borehole disposal should be consistent with the safety requirements outlined in Section 3. For short term disposal activities, such as a single disposal campaign, it is probably more appropriate and effective to apply licensing conditions rather than to issue specific regulations solely for the purpose of the development of a borehole disposal facility.

In any case the safety principles, requirements and criteria for waste disposal and for judgement of the acceptable level of safety need to be made known to the waste management organization (i.e. licensee) before starting the development of a facility. For example, requirements may be placed on institutional control after sealing. It is appropriate to give consideration to:

- Radiological criteria (e.g. dose constraints) and waste acceptance criteria such as specific activity per package or container, and total activity per single borehole or for the whole disposal site (taking into consideration the number of boreholes on a site), based on a (possibly generic) safety assessment;
- A demonstration programme for the disposal operations during commissioning, for example with the aim of avoiding misplaced waste packages that might be difficult to recover at a reasonable cost;
- Timescales for licensing to be considered and the period of institutional control, if required;
- Specific requirements on the control of waste packages and record keeping (e.g. long term preservation, archives) and reporting;
- Requirements on retrievability of the waste after closure;
- Periodic review of the safety of the facility.

4.2.2. Authorization

Licenses would only be issued when the acceptable level of safety has been demonstrated, with reasonable assurance, in compliance with the regulations. It is good practice for the licence to have sufficient flexibility to accommodate foreseen or possible changes in design, or increased knowledge. However, all design changes with significant impacts on borehole safety (e.g. changes to the waste acceptance criteria, backfill, cover) need to be based on a reassessment of facility safety and be implemented after the approval of the regulatory body.

Two main types of authorization could be carried out in respect to the development of a borehole facility:

- Development, upgrading and closure of a borehole facility or series of boreholes at an existing authorized disposal site;
- Development of one or a series of boreholes at a new disposal site.

In the first case the development of a new borehole is authorized as part of the amendment of an existing licence based on a reassessment of safety of the whole disposal site. In the second case the license is granted as for a new disposal facility based on a safety case demonstrating safety with reasonable assurance for the proposed disposal activity.

For a single disposal campaign it is recommended that all activities of the management plan are authorized at the same time in a single licence. This will assist the regulatory body in ensuring that all interdependencies are considered properly. Thus, it is appropriate for the conditioning of the sources for disposal, storage, transport, siting and preparation of boreholes, disposal operations, sealing and institutional control to be assessed and licensed as an integrated process.

In cases where such an integrated solution is not possible (e.g. long term operation of a borehole or subsequent construction of several boreholes on a site) a license may be issued for the disposal or for one or several steps separately. In any case it is important that all steps are taken into account in the review and assessment work and periodical reassessment of borehole safety is performed based on any new data and information available. As far as possible, decisions need to be reversible or compatible with anticipated future management steps. In particular, this is relevant for waste conditioning, which should be made reversible, at least until preliminary safety assessments have been reviewed and approved by the regulatory body and the disposal operation has gone through an appropriate testing programme.

The licence could also require reporting of the waste received and disposed of at the borehole facility. This will contribute to the development and maintenance of a national inventory of radioactive waste and will ease the transfer of knowledge to the future generations.

Depending on the national legislation the regulatory body may contribute to dialogue with the public or particularly interested parties leading up to the licensing process, e.g. according to the principles established for environmental impact assessments.

4.2.3. Review and assessment

The regulatory review and assessment may vary considerably depending on the magnitude of the disposal activity and the available national regulatory infrastructure. However, regardless of the scale and complexity of the disposal activities, it would be desirable for the regulatory function to be performed during the consecutive stages, namely siting, design, commissioning, operation, closure and post-closure of the borehole facility. It is the task of the regulatory body to review and assess the activities envisaged for each of these phases.

Regulatory reviews and assessments of borehole disposal safety need to give consideration to the following aspects:

- Definition of the minimum data and information required;
- Accuracy of the data and information presented;
- Demonstration of the level of safety with reasonable assurance, and the degree of confidence and robustness of safety case;
- Peer review of the safety case.

Performance of periodic safety assessment may be required by law or by the regulatory authority for existing disposal sites. This could be based on the need for updating the safety case with new information and data, or as part of the extension of the disposal facility with new boreholes, or in the light of monitoring results.

4.2.4. Inspection

The regulatory body needs to ensure that adequate control is provided at all stages in the development of the borehole disposal facility. This should be performed in accordance with an inspection plan developed for the specific purpose and activity to be controlled (e.g. construction, operation, closure).

Taking into account the specific features of borehole disposal (e.g. depth and operational period) the focus of the inspection activities needs to be directed towards the period prior to emplacement of the waste. This may require the presence of regulators at the disposal site during the operation and closure activities in order to ensure efficient control over the compliance with the license and operational procedures (e.g. acceptability of waste packages, their emplacement, etc.). This approach is particularly relevant for borehole facilities operated for a short period of time, due to the small quantities of waste involved and limited resources for operation, maintenance and regulation of the disposal site.

The actions and procedures to be followed by the operator in any case of non-compliance with established requirements needs to be specified and approved by the regulatory body.

4.2.5. Regulation of past practices

This section considers past practices in borehole disposal from a regulatory perspective. It is not clear that all past practices are consistent with the safety guidelines discussed elsewhere in this document. In this context it is particularly relevant to note that the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management requires contracting parties to report on past practices and possible interventions.

The purpose of a safety assessment of an existing waste disposal facility should be:

- First, to assess whether the facility satisfactorily provides protection from radiation to future generations in accordance with the basic principles [4, 8]; and

- Secondly, if appropriate standards are not met, to determine if there is justification to intervene at the facility, and to retrieve the waste or take other corrective action.

Straightforward application of these guidelines may in some cases suggest a need to carry out some corrective actions or to retrieve waste from the disposal facility. However, it needs to be emphasized that application of these criteria to potential future doses is far from straightforward. IAEA guidance on intervention states that the need to intervene should be based on justification and optimization [8]. Put succinctly, the concept is to do more good than harm.

In the current context of borehole disposal, this means that the potential future risks to individual members of the public needs to be balanced against actual risks to workers associated with the intervention. If the approach is applied to existing borehole disposal sites, it is likely to lead to a situation where one of the following options needs to be chosen.

Option 1: Carry out additional site studies and apply justified corrective actions

The first option would be to apply some corrective actions at the disposal facility. Many corrective actions that might be considered will only impact dose projections during the period of active institutional control. However, the most significant doses could be associated with long time frames, for which it is unreasonable to assume that active control of the facility will be in existence. Consequently, typical corrective actions are not expected to alter the long term dose projections of the facility. A slightly different approach would be to focus site characterization and data collection efforts to address issues raised by the safety assessment. However, while data collection activities may influence estimated doses from some pathways, they are unlikely to address all issues from all scenarios.

Option 2: Retrieval of waste

Evaluation of the advisability of this option needs to consider several issues. First, optimization of doses (ALARA) should be considered. This means that doses to workers during the retrieval of any waste need to be considered, and these should be optimized against the potential doses associated with leaving the waste in place. There is currently no clear guidance on an appropriate approach to carrying out such an optimization. In addition, if the waste is retrieved, it will eventually need to be disposed of somewhere. Such disposal would inevitably lead to potential exposures that need to be accounted for in the optimization assessment.

Option 3: Accept potential risks associated with the existing situation

If the risks and costs associated with corrective actions or waste retrieval outweigh the benefits, then it may be considered to be acceptable to leave the waste in place. In this situation the risks associated with the existing situation would be accepted, even if the projected doses exceed the dose constraints applied to new facilities of the same type. Such a decision should only be made based on a careful assessment of alternatives. While no corrective actions would be initiated, it would be prudent to enhance the institutional controls on local land use to minimize the likelihood of future exposures.

In the end the decision to carry out an intervention will need to be endorsed by the regulatory body, which will also need to consider the following aspects:

- Interventions should preferably only be done after the subsequent steps in the management of the waste has been decided upon and their consequences evaluated;
- All possible sites which are candidates for intervention within the Member State or a region within it have been investigated and a priority established;
- The implications of having to demonstrate compliance with additional regulatory requirements or requirements established in different regulatory regimes (transport, environment, nuclear, radiation and waste safety).

4.3. SAFETY APPROACH

4.3.1. Phased disposal facility development

It is appropriate to develop a disposal facility in an iterative phased process, taking into account the practical options available at each step, and with the ultimate goal of providing an acceptable level of overall safety and confidence in that safety. Decisions or measures taken to improve public acceptability or to reduce costs should not compromise the overall long term safety of the disposal facility.

4.3.2. Passive safety

A borehole disposal facility should be sited, designed, constructed and closed to provide the safety of the waste by passive means over the long term.

To assure safety over the long term it should be possible to close the facility and cease management of the facility at some time. The cessation of management implies that the facility as a source of radiation hazard is no longer under active control and actual impacts that might occur may no longer be verified by monitoring. Thus, the natural and engineered characteristics of the disposal system should be sufficient, on their own, to assure the safety of the waste and protection of humans and the environment. Importantly, an adequate level of passive safety needs to be demonstrated with reasonable assurance by safety assessments before closure of the facility.

In practice, it is expected that institutional controls, including land ownership and restrictions on site use, will be maintained for a period of time even after facility closure. For example these can facilitate monitoring in order to provide assurance and confidence in the safety of the facility. Institutional controls and monitoring are to be regarded as additional assurance measures.

4.3.3. Confidence in safety

A borehole disposal facility needs to be sited and designed so that the system features, characteristics and processes on which the long term safety depends are sufficiently well understood and reliable over suitably long time periods, at least over the times considered in the safety assessment.

As well as presenting technical estimates of total disposal system safety it is necessary to address the level of confidence in these estimates [24]. This will be facilitated if it is possible to identify the features and processes that provide safety and show that these and their interactions are sufficiently well characterized and understood. This understanding and confidence in a number of key features and processes will also facilitate more qualitative arguments concerning safety. In practice, a disposal system is likely to include several features on which high reliance can be placed considering that that the contribution to safety of other features, though expected, may not be reliably quantified.

4.4. SAFETY FUNCTIONS

4.4.1. Containment

Containment refers to the prevention of radionuclide migration such that they remain within or close to the engineered barriers for a sufficient length of time. The combination of engineered and natural barriers should provide a high level of containment of the radionuclides for a period commensurate with the hazard posed by the waste. The containment of the waste over an initial period ensures that the majority of shorter lived radionuclides will decay in situ.

Low volume, higher radiotoxicity waste can be placed in durable containers that will contain the waste for many hundreds or thousands of years. In all cases, geochemical, physico-chemical and biological retention processes are important containment processes, providing retardation of radionuclide transport in the geosphere. Evidence from natural analogues indicates that chemical retention processes can be effective over very long time scales but complete containment is not to be expected. Most systems will make use of a combination of physical and chemical barriers with multiple safety functions aimed at containment and isolation of the waste.

4.4.2. Isolation

Isolation means keeping the waste and its associated hazard away from the biosphere and resources used by humans, and also making it difficult for people to gain access to the waste. For disposal depths below those of normal human activities (typically 30 m) isolation is primarily provided by the geosphere. However, for depths closer to the surface, institutional control becomes increasingly important as a safety function.

Institutional controls also contribute to the isolation of the waste and are likely to be most effective for a borehole at a site with an existing security infrastructure, for example at a nuclear facility.

The engineered and geological barriers should provide sufficient isolation of the waste from the accessible human environment over long timescales, although some migration of a fraction of the longer lived and more mobile radionuclides may be inevitable.

Complete isolation cannot be guaranteed over very long time scales. The reliability of engineered barriers is difficult to prove over long timescales and, given sufficient time, natural processes such as tectonic uplift and erosion may remove enough of the overlying rock to bring the waste close to the surface. The selected geological environment should be sufficiently stable and the engineered barriers sufficiently robust that safety criteria can still be met with reasonable assurance.

Also, human intrusion in the long term is inherently unpredictable but may affect the level of containment and isolation of the waste. However, some actions can be taken at the time of borehole disposal to lessen its probability or consequences. It is likely that a borehole disposal facility operator would opt for actions to reduce the probability of intrusion rather than its consequences, as suggested by ICRP [18], for example by choosing an appropriate depth and design of disposal system.

4.4.3. Multiple safety functions

Although the safety of a borehole disposal facility will ultimately be judged by global measures of total system performance, the disposal concept has certain basic safety features that require separate attention. The various safety functions may be engineered, chemical, geological or administrative and their reliability should be evaluated in the safety assessment. This together with monitoring and assurance procedures builds confidence in the robustness of the system and that safety is not overly reliant on any individual safety function.

The natural and engineered barriers can be designed to provide for long term safety by means of multiple safety functions that are not unduly dependent on each other. This can be achieved by ensuring that the functions of the engineered and natural barriers depend on diverse physical and chemical processes and are assured by quality management procedures. In this way, the overall safety of the system should not be strongly dependent on the performance of any one component. A typical borehole facility design incorporating multiple safety features is illustrated in Figure 1.

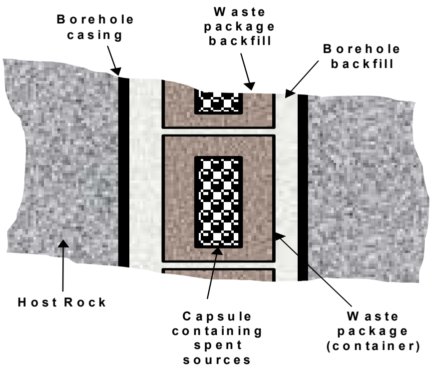

FIG. 1. Schematic illustration of possible components of a borehole disposal system.

5. IMPLEMENTATION OF THE SAFETY STRATEGY

This section sets out guidance related to the implementation of the safety strategy in order to achieve an acceptable level of safety and confidence in the safety of borehole disposal facilities. The section addresses the framework for borehole disposal, safety assessments and the safety case, and characterization and disposal facility implementation.

5.1. FRAMEWORK FOR BOREHOLE DISPOSAL

It is recommended that borehole disposal facilities are developed according to a step by step approach, supported by iterative evaluations of the design and management options, system performance and overall safety.

A step-by-step approach to disposal facility development enhances the quality of the technical programme and the technical decision-making. It provides a framework in which sufficient technical confidence in the feasibility and safety can be developed at each step of the development. This confidence is refined by iterative design and safety studies as the project progresses [25, 26]. The process needs to allow sufficient time and opportunities for the collection and interpretation of the relevant scientific and technical data, the development of designs and operational plans, and the development of a safety case giving reasonable assurance of operational and long term safety.

The step-by-step approach also allows opportunities for independent technical reviews, and political, public and other stakeholders involvement.

5.2. SAFETY ASSESSMENT AND THE SAFETY CASE

This section presents an overview of post-closure safety assessment and the development of a safety case. Operational safety is not considered here, but it is nevertheless regarded as particularly important because of the relatively high specific activity of disused sealed sources.

Safety assessment is an essential part of the development of a borehole disposal facility. Safety assessments can be used for a number of different purposes at various stages of the development of a facility. At the early stages, safety assessment can be used to determine the feasibility of the different borehole disposal concepts, to direct site investigations and acquisition of additional data, and to assist in decision-making on site selection. During later stages, safety assessment can be used to assist in optimization of the borehole system design by carrying out assessments for various combinations of alternative waste forms, waste packages, depths, operational, closure and post-closure measures.

5.2.1. Demonstrating compliance with safety requirements

Demonstrating the safety of a waste disposal facility with reasonable assurance is primarily the responsibility of the operator. There will be formal regulatory processes to follow and there may also be requirements to satisfy environmental impact assessment legislation. Also there may be the need to address the issues of broader public acceptance, which would require dialogue with groups of stakeholders.

This document addresses the more formal processes of demonstrating safety with reasonable assurance required by the regulatory process, but this should also be relevant to other stakeholders. The regulatory process requires the safety arguments to be documented. The internationally recommended approach [24] is to present these arguments by way of a documented safety case that provides the arguments why the facility is considered to be safe and includes various assessments and analyses discussing their relevance and their strengths and weaknesses.

During the process of developing any radioactive waste disposal facility, including borehole facilities, the safety arguments will evolve as the project progresses. At the initial planning stage limited information and assessment will be available and the level of confidence in the acceptability of the facility could be limited. The safety case will develop, as more information and assessment results become available. At some stage, the available information may indicate problems or shortcomings with the site or design, which will have to be addressed by way of an iterative process of options appraisal and assessment. The process should identify areas where further work is necessary or where changes are needed to the site or design.

The first task is to identify the intended inventory and show that this will cover the sources or wastes types that are expected to arise. It needs to discuss the appropriateness of the type of facility planned and how it is proposed that the facility will operate. For instance it could be intended to operate the facility periodically on a campaign basis or on an ongoing basis. It should also address the location of the facility and how it will cater for the various locations at which disused sources or other waste types are expected to arise. Having addressed why a borehole facility is a suitable option for the wastes expected to arise, it is then necessary to address the actual safety of the proposed facility.

The safety arguments need to address how the facility will meet the various safety requirements discussed in Section 3. This essentially entails a demonstration with reasonable assurance that:

- The site has appropriate characteristics;
- The design of the facility including the engineered and natural barriers will provide an adequate level of isolation for the proposed inventory;
- The overall system will provide adequate containment by limiting the release and migration of radionuclides from the facility to the biosphere;
- Radiological impacts to critical groups are within the established dose/risk limits.

The design of the overall facility should aim to have a good balance between the various engineered, natural and institutional safety functions. There should be sufficient evidence presented to demonstrate with reasonable assurance that the various safety functions will be able to perform as required and that the overall management approach provides confidence in the design and its implementation.

In addition to showing that the facility design will be able to meet the various technical requirements, there should be an assessment of the expected performance of the facility over time including the expected radiological impact of the facility to the environment and to members of the public. The assessment needs to consider the normal or expected evolution of the facility and the site over time. In addition it is appropriate to consider the potential impacts of relevant natural disruptive events, such as floods or earthquakes. Finally, an assessment may need to consider the impact of possible future human activities, which could give rise to additional exposures or change the normal evolution of the facility.

Such assessments will make use of information about the site, the facility design, the intended inventory and the biosphere. They will also make use of information and models to describe and analyse the processes of degradation of the engineered barriers, migration of radionuclides from the waste and through the geosphere and biosphere, and subsequent radiation exposure. There will be uncertainty associated with these assessments, both where data is limited and in the models themselves. Also, there will also be uncertainty concerning the scenarios selected for assessment. It is important that the assessment process or the safety case carefully addresses these uncertainties with a view to ensuring that they are properly identified, that appropriate efforts are made to reduce them where possible and that they are quantified to the extent possible. The presentation of the assessment should give consideration to the identification and treatment of associated uncertainties.

An important aspect to be considered in the safety case and its supporting assessments and analyses is the level of quality in all aspects of the project that impact on safety. The safety case needs to provide evidence that the various processes such as site selection and characterization, facility design and safety assessment are all subjected to appropriate quality management programmes. In addition, the technical and engineering aspects of the project should be subjected also to appropriate quality regimes in the manufacture of equipment, construction of facilities and in all the associated testing and demonstration processes.

The safety case needs to address the safety of the facility in the long term including arrangements for closure of the facility and any subsequent period of institutional control, together with any associated monitoring. The information deemed relevant to the future safety of the facility and necessary to be retained needs to be compiled and placed under suitable storage arrangements. The adequacy of the safety assessment and safety case should have been subject to regulatory review and approval.

5.2.2. Safety assessment methodology

Safety assessment is an iterative process that may suggest the need for additional data or for a re-evaluation of the conceptual design. It involves both quantitative analysis and expert judgement, and is a key input to decision-making on the suitability and acceptability of a borehole disposal system. Safety assessment is a multi-disciplinary activity requiring expertise from a range of fields including geology, seismicity, engineering and radiological protection.

The long term safety assessment methodology for near surface disposal developed under the ISAM Co-ordinated Research Programme [10] is widely accepted to provide an appropriate basis for the safety assessment of disposal facilities including boreholes. This methodology has been applied in the ISAM illustrative test case on a borehole disposal facility and in a preliminary assessment of the BOSS (Borehole disposal Of Spent Sources) disposal concept [6]. The key components of the methodology are outlined below and illustrated in Figure 2:

- Definition of the safety assessment context (feasibility studies, derivation of waste acceptance criteria, etc.);
- Description of the borehole disposal system (near field, far field and biosphere);
- Development and justification of scenarios (normal and alternative);
- Formulation and implementation of conceptual and mathematical models;
- Calculation of the consequences of relevant scenarios;
- Analysis and interpretation of the calculation results;
- Iterative re-evaluation of the assumptions, design, or inventory based on the interpretation of the assessment.

Safety assessment is a process to assist in demonstrating the safety of a borehole facility with reasonable assurance through comparison with safety requirements and criteria (dose and risk constraints and technical design requirements). Therefore the safety assessment should evaluate the natural evolution of the facility and the possibility of human intrusion.

Important aspects to consider in the assessment include:

- The decay of radioactivity in the sources;
- The progressive degradation of the waste form, packages and other engineered barriers;

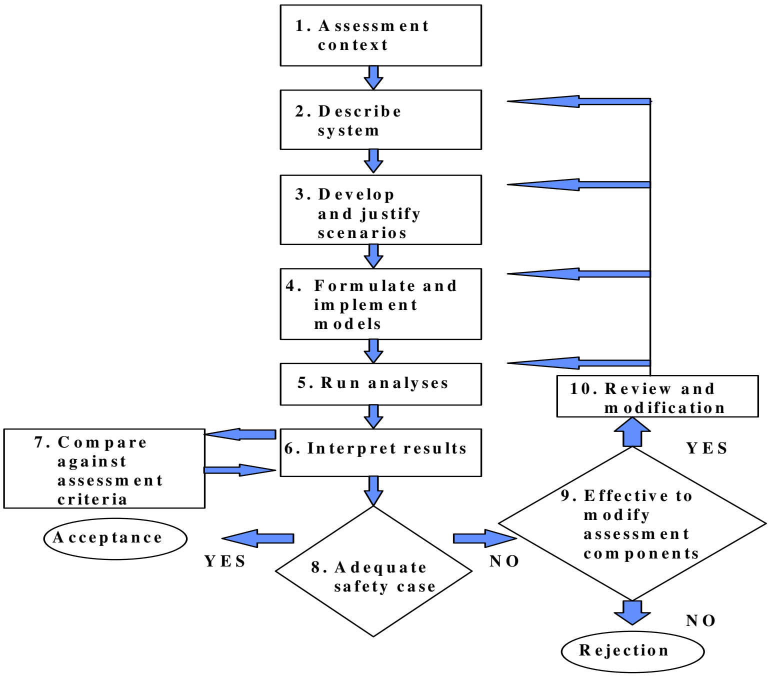

FIG. 2. The ISAM safety assessment process. Adapted from Ref. [10].

- The mobilization of radionuclides from the waste package and borehole;
- Chemical transport and interactions of radionuclides within the engineered barriers;
- The movement of water around the waste packages and in other formations above and below the host rock;
- The transport and retardation of radionuclides within the rock–water system;
- Dilution and dispersion of radionuclides in the environment;
- Uptake pathways in the biosphere leading to radiation doses to people (and impacts on the environment);
- The impact of other events and processes that could disturb the expected evolution of the system.

Safety assessment of a borehole disposal facility begins with determination of the intended inventory, with a view to determining whether the system can provide an acceptable level of safety in a cost-effective manner. The end-points of an assessment need to be well defined and correspond with the safety assessment purpose and the associated regulations. They should take account of the time scales and critical groups that are appropriate.

At the outset it is important to define the extent to which the assessment is designed to provide a realistic estimate of potential impacts or whether a more cautious or pessimistic assessment is required.

The description of the borehole disposal system covers the near field (e.g. waste inventory, waste types, waste forms, disposal practices, engineered barriers, facility dimensions); the geosphere (e.g. lithology, hydrogeology and transport characteristics); and the biosphere (e.g. exposure pathways, human habits and behaviour). It is an important step in the assessment, and needs to be carried out as realistically as possible. The associated assumptions need to be clearly identified and justified, including those relating to the type of society, and future human habits.

The time frame for the post-closure safety assessment needs to be selected, recognising inherent limitations and uncertainties in assessment approaches, as well as constraints on the scientific credibility of long term estimates of disposal facility performance imposed by large scale environmental changes.

It is necessary to ensure that the data collected are pertinent to the assessment context. The limited availability or adequacy of data is an important factor in many safety assessments. Thus when developing the system description, it is important to be aware of and to document the assumptions made and the associated uncertainties.

The safety assessment for a waste disposal facility needs to address the performance of the system under both present and future conditions, including anticipated and less probable events. This means that many different factors (e.g. conceptual model uncertainty, parameter uncertainty, long time periods, human behaviour and climate change) need to be taken into account and evaluated in a consistent way, often in the absence of quantitative data. The generation of scenarios needs to provide a comprehensive picture of the possible evolutions of the system based on the assessment context and system description. The choice of appropriate scenarios and associated conceptual models is very important and strongly influences the subsequent safety assessment.

There is no international consensus on the applicability of specific safety indicators other that dose or risk; or cut off times for safety assessments of disposal options. However, time frames over which various indices would be appropriate have been discussed internationally. Practically speaking, safety assessments are often conducted in such way that the peak individual dose or risk is covered.

The safety assessment process is iterative and the first pass through the process would normally be followed by one or more iterations. This promotes consideration of improvements to the disposal system regardless of how favourable the initial results appear. The iterations should proceed until the assessment is judged to be adequate for its purpose. Furthermore, new site-specific data need only be collected to the extent that they are required in order to provide an adequate basis for the decision.

It is important to note that the acceptability of a borehole disposal system should not be judged solely on compliance with dose or risk constraints. More qualitative, parallel lines of evidence and reasoning are important in order to support results of the safety assessment and to provide illustrations of the overall safety of the disposal system [24].

5.2.3. Generic safety assessment approach

The IAEA has overseen the development of two preliminary post-closure safety assessments for the borehole disposal concept [6] and is in the process of developing a more comprehensive generic safety assessment as part of the AFRA programme.

The general objective of a post-closure safety assessment is to determine what impact the disposed waste will have on individuals and their environment as a function of time. Generic assessments are relevant to early iterations of the safety assessment process and have the potential to facilitate this process by:

- Identifying the key safety features of the borehole disposal concept and thereby helping to define the characteristics of the system and additional data (e.g. borehole depth) that need to be addressed in the development and licensing of the concept;
- Developing an understanding of the contribution of natural and engineered barriers to the overall safety of the disposal concept;
- Providing useful strategic information into the further development of the concept, e.g. waste emplacement configuration, engineered barrier configuration, influence of different environmental conditions on the performance of the concept;
- Providing an indication of favourable geosphere and biosphere characteristics as input to site selection and characterization;
- Indicating the radionuclide inventories that are likely to be acceptable from a radiological safety perspective;
- Providing practical guidance in the form of a blueprint for the structure, content, models and data requirements for site-specific safety assessments;
- Improving the confidence of policy makers, the scientific community and other stakeholders in the borehole disposal concept as a long term management solution.

A generic approach has proved useful for defining reference activity limits for near-surface disposal facilities.

The driving force behind using a generic approach to safety assessment is that borehole disposal is relatively straightforward to implement but it is not necessarily straightforward from the perspective of safety assessment. The aim of the ongoing IAEA work is to facilitate the development and safety assessment of borehole facilities, especially in countries that lack an infrastructure for the long term management of radioactive waste.

The generic approach represents a spectrum of possible site conditions (e.g. geological, hydrogeological and climatic) and disposal features (e.g. borehole depth, waste package) to cover the range of possibilities. Justified parameter values from operational experience with borehole facilities as well as the literature are used as far as possible. Different combinations of disposal system components and characteristics enable the definition of 'envelope' assessments to guide the site-specific implementation of the concept. If the characteristics of a proposed facility lie within one of these envelopes, then a preliminary indication of the long term safety can be inferred. Of course sufficient engineering design and site characterization information would need to be available to determine whether the site-specific system lies within a particular envelope. An example set of combinations of disposal system characteristics for generic safety assessment is illustrated in Figure 3.

Since the waste packages are likely to represent a small fraction of the cost of the overall programme, there is merit in over-designing them so that they would have excellent performance in all geological environments. To ensure this, it is appropriate for the package to make use of high quality materials such as copper or stainless steel. Thus the generic assessment would just need to consider a single set of near-field engineered barriers, although it would be necessary to consider a range of waste inventories. A number of generic geosphere environments would be considered with the waste located in either the saturated or unsaturated zone (Figure 4), and at different depths. Finally, a range of generic biosphere environments would be evaluated.

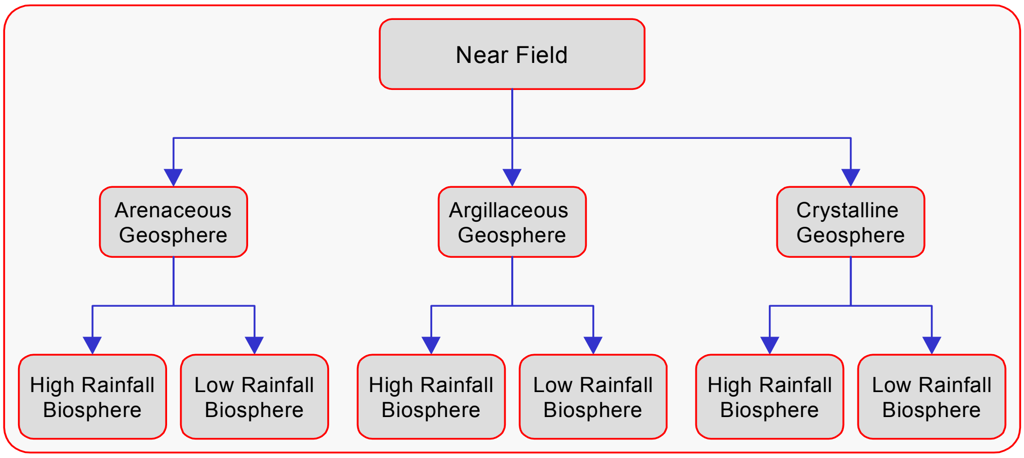

FIG. 3. Example of a set of combinations of disposal system characteristics for a generic safety assessment of the borehole disposal concept.

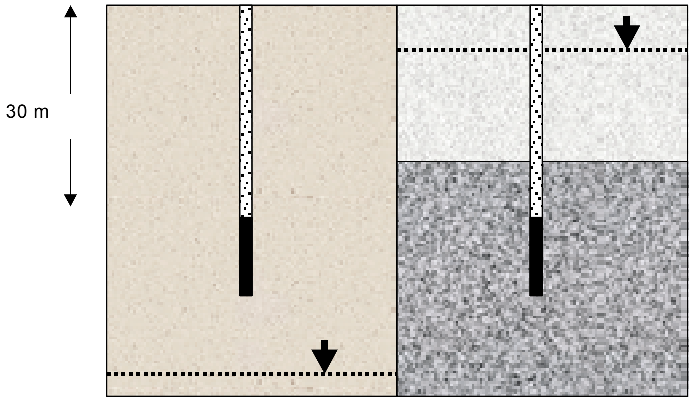

FIG. 4. Schematic illustration of two shallow borehole disposal concepts: left in the unsaturated zone, right in a low permeability formation below the water table. The dashed lines show the position of the water table.

It is hoped that the generic approach will reduce the resources and expertise required to assess the safety of a borehole disposal facility. It would necessarily involve conservatism and good safety margins. The envelopes would be used in assessing the safety of particular disposal facilities by a process of showing that the facility design, the inventory, the site and all the other relevant characteristics fall within the assessment envelope.

The methodology for establishing such envelopes and the demonstration of compliance with reasonable assurance remains to be fully developed, tried and tested, but in principle such an approach offers the possibility of providing a cost-effective demonstration of facility safety.

The generic approach could be of particular use at the concept development stage and in support of site screening. Also it could be useful in evaluating any limitations on the radionuclide inventory and in contributing to the confidence of any site-specific safety assessment. The comparisons with the reference borehole facilities (envelopes) needs to be performed with caution and should ensure consistency of the assessment context, site and borehole facility characteristics, scenarios, models and relevant information and data used.

The most important tasks are building confidence in the reference borehole systems and showing that the real borehole facility falls within the boundaries and assumptions of the reference borehole case. It is also necessary to consider the qualitative aspects of the safety assessment such as the robustness of the multiple safety functions, quality assurance, and multiple lines of reasoning, before making a final decision on the acceptable level of safety of the real borehole facility.

The ISAM borehole test case could be considered as a basis for one of the reference borehole concepts. This relates to the disposal of typical sealed sources in Africa at a depth of 40–100 m in an unsaturated zone for an arid climate. Based on the scenarios for borehole disposal facilities developed in the ISAM programme, the BOSS feasibility study [6] and safety assessments for Radon type facilities [5], the following relevant scenarios could be considered (see Table 1):

- Normal evolution under expected conditions together with an assumption that a water well is drilled close to the site;
- Natural disruptive events (e.g. erosion);
- Inadvertent human intrusion of the borehole disposal zone (e.g. exploratory drilling).

Under some circumstances (primarily shallow depths), inadvertent human intrusion scenarios can be more important than normal evolution scenarios. Consistent with ICRP 81 [18] the impact of deliberate intrusion is the responsibility of those intruding and is considered to be beyond the scope of generic post-closure safety assessment. The types of inadvertent intrusion that might be envisaged for a borehole facility include:

- Excavation of shallow facilities (e.g. by deep building foundations, deep cuttings for roads or railways, cut and cover tunnel construction, standard tunnelling, or open cast mining); and
- Exploratory boreholes (e.g. water or natural resource drilling), which could affect borehole facilities regardless of depth.

At depths below about 30 m, waste disposal would be below the ‘normal residential intrusion zone’ as defined by the NEA [25]. Consequently for such relatively deep borehole facilities it is likely that the only mode of potential human intrusion would be by a drilling intrusion.

Several other potential Features, Events and Processes (FEPs) could potentially have an effect on the long term disposal system performance of the borehole facility including [7]:

- Poor quality control;
- Seismic events;
- Environmental change;
- Societal change resulting in alternative land uses, e.g. fish farming;
- Intrusion by animals (e.g. termites) and plant roots;
- Radiation effects including irradiation-induced damage of engineered barriers and the radiolysis of water leading to hydrogen production;
- Gas generation due to corrosion and alpha decay;
- Degradation of engineered barriers due to chemical, geochemical and biogeochemical reactions;

TABLE 1. EXAMPLES OF REFERENCE SCENARIOS FOR BOREHOLE DISPOSAL FACILITIES

Depth	Normal Evolution	Natural Disruptive Events	Human Intrusion			
			Excavation	Drilling	Dwelling	Farming (using water from a well)
From 0 to 30 m	Contamination of aquifer /drinking well Contamination of water bodies	Erosion Seismicity Bioturbation	√	√	√	√
From 30 m to 100 m	Contamination of aquifer /drinking well Contamination of water bodies	Seismicity Bioturbation		√		√
Greater than 100 m	Contamination of aquifer /drinking well Contamination of water bodies	Seismicity		√		√

- Short-circuit groundwater pathways, for example along the interfaces with the borehole liner;
- The effects heat loading on the system integrity and water flow.

Thermal effects are likely to be particularly important for high activity sources, and will need to be considered in the design and assessment of the facility. Possible deleterious effects of high heat output include:

- Natural convection of water within the borehole and in the subsurface, with associated higher potential for migration of radioactive contaminants;
- Potential for enhanced degradation of engineered barriers materials;
- Potential to change chemical equilibria in ways that lead to increased mobility of key radionuclides;
- Potential for alteration of the surrounding geological media, particularly clays.

Disposal of high activity gamma sources leads to the potential for alteration of the engineered barrier materials. Radiolysis may cause the generation of chemically aggressive conditions that could increase the rate of corrosion of the engineered barriers (e.g. steel or other metal containers, components, etc.). These effects should be considered in the post-closure safety assessment of borehole disposal facilities. Specifically their impact on waste acceptance criteria (e.g. for a waste package) needs to be assessed. For example, this may lead to segregation of high activity gamma sources from long lived sealed sources.

The distribution of specific radionuclides within and between boreholes could be of importance for the long term safety of the facility. It may be beneficial to distribute long lived sources in a number of borehole facilities to lower the potential impact at any receptor point. Similarly, differences in borehole performance may be associated with the location of the source within a borehole. Depending on the dominant scenario, longer lived sources may be placed at the bottom of the borehole. All these design options need to be evaluated on the basis of a safety assessment.

In future it is hoped that the continuing IAEA programme of generic assessments will provide practical guidance that facilitates the safety assessment of specific proposals for borehole disposal facilities.

5.2.4. Safety assessment outcome

The quantitative outcome of a safety assessment should be compared with the criteria discussed in Section 3. There should be a demonstration with a reasonable level of assurance that the dose constraint will not be exceeded for the expected normal evolution of the facility and its site. A reasonable level of assurance should be taken to mean that the process has been subjected to appropriate levels of review, that sufficient justification has been provided for the data, models and scenario assumptions and that all the processes have been subjected to an appropriate quality management programme.

When making a comparison of the results of assessments with numerical criteria, consideration needs to be given to the margin of safety indicated by the assessment. In the case where results indicate doses or risks close to the limiting values, careful consideration needs to be given to the assessment to ensure that overly conservative assumptions have not been made. If the results are considered to be realistic estimates of likely performance and the results are still close to the limiting values, further consideration should be given to the design. Alternatives that could provide a higher margin of safety or greater assurance should be explored.

The safety analyses needs to be documented and subjected to regulatory review. They need to demonstrate with reasonable assurance that the various numerical criteria will be respected, and that each element of the system is properly designed to meet its performance requirements. Moreover, the safety of the overall facility needs to be robust and optimized.

5.3. DISPOSAL SYSTEM IMPLEMENTATION

This section sets out preliminary guidance for the implementation of borehole disposal based on international experience to date.

5.3.1. Waste acceptance criteria

Waste accepted for borehole disposal should conform to criteria that are consistent with the operational and post-closure safety cases for the disposal facility. The waste should be in a solid form with stable chemical and physical properties, and should be compatible with the engineered and natural barriers.

It is expected that waste acceptance criteria will be developed consistent with the borehole disposal concept and general safety arguments. In due course, these may be refined to take account of the site and design-specific safety case as this develops. The waste acceptance criteria will usually specify radionuclide or radioactivity limits and waste matrix or encapsulation requirements and container properties. Also, for high activity sources, acceptance criteria will need to consider the radiation and thermal characteristics.

5.3.2. Site selection

Locating a suitable site for a borehole disposal facility involves consideration of scientific and technical, socio-economic and planning factors in equal measure. An initial list of possible sites might be identified on the basis of scientific and technical factors, socio-economic and planning factors or a combination of these. Sites may arise in the selection process because they are the location of existing nuclear, waste management or government facilities and these are sometimes given high weighting on the grounds of availability, practicality and institutional control.

It is accepted that, in many countries or regions, resources for detailed site characterization may be limited. This section thus considers the essential aspects of site characterization that would need to be carried out to obtain information for design and safety assessment purposes.

In general it is desirable to determine the potential suitability or acceptability of a site as quickly as possible with use of minimum resources. This is especially relevant for countries where accidents with sealed sources have occurred and a safe and long term management solution is required.

Basic generic guidelines for siting radioactive waste disposal facilities are presented in IAEA publications [27, 28]. However, the borehole concept requires some interpretation of these guidelines. The use of borehole disposal may be the preferred option where surface area is limited and other disposal methods are precluded. Regardless of the types of source in the borehole facility, or the depth of disposal, the functions of the natural barriers are to:

- Provide radiation shielding between the sources and the biosphere;
- Isolate the waste from the activities of people and from dynamic processes on Earth's surface by disposing of waste at a sufficient depth;
- Provide a physically and chemically stable environment to allow the engineered barriers to provide a reasonable period of containment;
- Limit groundwater access to the waste;
- Retard the migration of any leached radionuclides by ensuring low water flow and high sorption of radionuclides;
- Dilute and disperse any migrating radionuclides before they reach the biosphere.

These functions can define favourable geographical, geological and groundwater environments, for example with the following characteristics:

- Permanently unsaturated (predictable with confidence over the relevant containment period) and/or low permeability saturated host rocks at an appropriate depth;
- Low hydraulic gradients in the host rocks;
- High sorption capacity;
- Favourable groundwater geochemistry, e.g. regarding waste package corrosion;

- Lack of significant groundwater (aquifer) or mineral resources (including potential deep hydrocarbons);
- Low erosion rates and lack of susceptibility to flooding, occasional high rainfall events and land instability. It is advisable to locate the active part of the borehole disposal system below the erosion base;
- Lack of susceptibility of the environment to climate change effects over the containment period of relevance (e.g. sea level fluctuations, river valley deepening);
- Local tectonic stability: not close to active fault lines or in areas prone to frequent seismic activity;
- Simple geological structure and hydrogeological system, avoiding areas of excessive geological complexity, which could be difficult to characterize and which may limit the degree of confidence in safety assessment results.

For deep boreholes, suitable host rock formations are likely to contain old, possibly saline, groundwater indicative of very slow flow and little mixing with shallower waters over past times equivalent to the containment periods of interest. Shallower boreholes may also be sited in low permeability formations, provided that they are not affected by significant fracturing and the ingress of surface waters (e.g. as sometimes found on unloading of previously deeply buried clays near the ground surface). They may also be in more permeable rocks, in stable hydraulic environments above or below the water table, providing the region shows to possess reliable climate stability over time periods of concern for containment.

Where resources are limited, it would be prudent to concentrate on the most robust safety concepts and on looking for sites with the simplest geological and surface environments. The objective would be to search for areas that quite obviously had high potential, on the basis of readily available first-order information, to have all of the characteristics defined above with a high level of certainty. First-order information means existing geological, topographical and hydrogeological mapping data, climate records and other environmental survey data. Essentially, this means looking for sites reflecting the upper end of the spectrum for each positive characteristic. The objective is to minimize the uncertainty that would be brought about by limited site investigations. A more complicated site might appear marginal or uncertain from first-order data. It would then be necessary to address each aspect of variability or uncertainty in a comprehensive site investigation if sufficient confidence is to be placed in a safety assessment. In many regions, first order information in the form of detailed national surveys and maps may be scarce, which puts an even greater burden on finding obviously simple, stable regions. However, if sufficient resources were available, it would also allow the examination of more complex sites, thus extending the scope of siting possibilities.

A disposal site would normally need to be accessible by road or rail and have the necessary local infrastructure (energy and water supplies) for constructing and operating the facility.

Where possible, areas with intensive agriculture, high population densities or on the fringes of expanding urban areas should be avoided.

The geological environment should be amenable to simple borehole construction using standard drilling and completion practices. Rock and deep soil formations that have poor stability for boreholes should be avoided, particularly for the host unit. Where possible, preference should be given to formations in which it is practical to place good behind-casing seals or grout-to-rock seals.

5.3.3. Site characterization

Once preferred areas or sites have emerged from the site selection process, the next steps would involve field activities, in particular the confirmation of simple geological structure and hydrogeology by surface mapping. The scale of mapping would be determined by the nature of the structures in the area. A geological, hydrogeological and hydrological model of the area would normally be developed from the mapping and from existing data, and used to identify target disposal zones at depth.

The extent of the site characterization needs to be commensurate with the number of disposal boreholes envisaged for a site and their separation. If boreholes are to be located at an existing near-surface repository site then much of the site characterization data is likely to be already available.

A pilot borehole would normally then be drilled at the preferred site, to a depth greater than the envisaged disposal zone. For proposed shallow borehole disposal, this would normally extend to the aquitard supporting the water table, if it is deeper than the disposal zone. For deep boreholes, a pilot hole might typically extend 50–100 m deeper than the base of the disposal zone, to confirm that there are no structures or hydrogeological features (e.g. underlying high pressure zones) that could affect performance. The objective of the pilot borehole would be to gather data on rock hydraulic conductivities, hydraulic gradients, groundwater flow rates and groundwater chemistry. The borehole would normally thus be designed to take core in (at least) the host formation, and should allow water sampling, ideally with flow-meter measurements, and standard geophysical logging.

Further shallow boreholes may be needed, distributed in the surrounding area, to determine the morphology of the water table and how it varies seasonally. Compilation of this information should give a clear indication of the nature of the groundwater regime and of the physical and chemical properties of the host formation. This will be used in the subsequent safety assessment, a component of which will be an analysis of long term groundwater flow at the site. If sufficient resources are available, it may be useful to investigate deep structures by local seismic surveys to help determine optimum locations for multiple disposal boreholes.

The nature of the groundwater system will depend on the hydrogeological properties of the rock formations and the climatic environment of the disposal site. In temperate regions with average rainfall, disposal zones in boreholes more than a few metres to tens of metres deep will enter the saturated region where groundwater flows in response to local hydraulic gradients and the hydraulic conductivities of the rocks. In more arid environments, water tables may be much deeper, perhaps even hundreds of metres deep, but the disposal zone may be contacted by permeating waters moving slowly down to the water table. In some arid to hyper-arid regions, water may be present even at quite shallow depths, but could be saline, with salinity increasing with depth. In the latter case, deeper saline waters may be exceptionally stable, with little or no flow.

5.3.4. Disposal facility design and construction

Performance assessments and safety assessments are important tools in demonstrating the optimization of the facility design for potential sites and the types of waste to be disposed. The expected behaviour and performance of the natural barriers in containing radionuclides has implications for the required level of engineered containment and the way in which waste emplacement and borehole sealing operations should be carried out.

A prime objective should be to design packages that provide the requisite levels of containment, while involving the minimum handling of the sources they contain, and designed to bear the mechanical loads associated with handling and stockpiling.

The choice of safety concept will affect the design basis for a borehole disposal facility. Together, design and safety concept will depend upon a number of factors including:

- The number, activity and thermal output of the sources;
- The period of time over which the sources will arise and the facility will need to be operational;
- Operational requirements, e.g. whether the facility is to be operated continuously, or on a campaign basis;
- The types of sources and their radionuclide content (the design should be commensurate with the category of the waste);
- The availability and potential capacity of suitable disposal environments;
- Design and dimensions of the waste packages;
- Possible environmental impact;
- The potential for human intrusion;
- The availability of appropriate drilling and engineering technologies.

Selection of an appropriate design for a waste package is essential for the pre-disposal and disposal period as it provides containment for the sealed sources during their storage, transport and disposal phases. The waste package provides the initial containment and its long term performance can play a key role in the overall performance of the borehole disposal system. The waste package durability will depend on the properties of the engineered barriers and their interactions. In terms of the operational activities associated with a borehole facility it is important to consider the:

- Corrosion and radiation resistance, durability, and compatibility of materials.
- Dimensions, weight limitations, filling arrangements in the container, emplacement and backfilling of the containers in the facility.

An example of a possible set of engineered barriers is shown in Table 2. Such engineered barriers could provide a substantial degree of containment and limitation of migration of radionuclides from the facility. It is difficult to evaluate with confidence how long each of the potential containment functions might last. A highly conservative safety concept might take no credit at all for containment within the borehole materials after emplacement, relying instead on the natural barrier. However, a well designed and constructed system of multiple containment barriers should be expected to form a reliable component of a safety concept. Thus, a safety case should be able to take some credit for a period of containment within the borehole itself, as discussed below.

The container backfill properties contribute to the performance of the waste package and the limitation of radionuclide migration. Therefore it is important to ensure that the selected backfill material has low hydrological conductivity to limit the advective flow of water.

TABLE 2. EXAMPLE COMPONENTS OF BOREHOLE ENGINEERED BARRIERS

Component	Possible safety 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 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 backfill
Container backfill /matrix within which sources may be embedded (e.g. cement grout or lead)	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 backfill surrounding containers (e.g. cement grout)	Control corrosion rate of containers; act as a sorption matrix and diffusion barrier controlling movement of radionuclides out of packages
Metal or plastic **borehole casing** supporting borehole walls during drilling or emplacement operations	Prevent access of groundwater to waste packages until casing corroded or degraded
Borehole seal: long (several m) clay or cement plugs placed in the casing above the disposal zone	Seal waste disposal zone from shallower regions of disposal system and prevent vertical, short-circuit release pathways

The borehole casing is able to contribute to the performance of the facility in the short term by keeping the borehole dry, ensuring constant volume in the facility, and facilitating emplacement of the waste packages. Although little credit is generally given to the casing as an engineered barrier in safety assessments, the casing may provide additional containment and its selection should take account of the groundwater chemistry and the properties of the geological surroundings. To fulfil its functions the casing needs to be inserted in the borehole facility straight as a continuous unit with proper sealing between the different casing units. If the borehole is within a saturated zone then the casing needs to be sealed at the bottom to ensure dry conditions for emplacement of the waste packages.

Depending on the geology there may be significant voids between the casing and the borehole. These voids could easily facilitate infiltration of water and influence its long term safety and therefore need to be sealed. Sealing is also required for:

- Filling the voids between the waste packages and the casing; and
- Prevention of water ingress from the bottom of the facility.

In addition, sealing can help to reduce human intrusion into the disposal facility. Other design measures that could be considered to reduce the probability or consequences of intrusion are:

- Siting of the facility away from areas with currently recognized subsurface resource potential;
- Use of increased depth of disposal to isolate the waste as far as practicable (e.g. disposal at the bottom of the borehole);
- Minimization of the surface area and access to the borehole to the extent possible;
- Selection of a layout to minimize the impact of an intrusive event;
- Use of thick concrete or metal plugs above the waste emplacement zone and/or above the borehole;
- Use of extra strength waste containers;
- Use of durable physical marker systems on the surface;
- Conservation and communication of information about the location, contents and hazard.

Whatever design features are incorporated to minimize human intrusion, it is recognized that the small footprint of borehole facilities at the surface, intrinsically limits the probability of intrusion compared to near-surface repositories.

During the siting, design and development of the borehole facility, a number of site, design and operational options will be available. These should be considered in terms of the overall disposal system design with a view to obtaining an optimum balance of containment, isolation and limitation of migration from the facility within reasonable financial constraints. The multiple safety function approach should be utilized and the safety of the facility should not rely unduly on a single barrier or safety function. The various design options should be subject to safety assessment to assess compliance with the dose and risk constraints. If this iterative process has been carried out and a reasonable assurance has been obtained that the dose and risk constraints will be complied with, the safety of the system can be considered to be optimized.

Finally, there should be high level of assurance that the facility is developed and constructed in accordance with the design and its associated technical specifications. All testing and inspection requirements should be fulfilled and any deficiencies rectified.

5.3.5. Depth of disposal

A key distinguishing feature of borehole disposal is that it is not limited to the depth ranges considered for near-surface disposal (metres to tens of metres) or geological disposal (hundreds of metres). On the contrary, it is relatively straightforward and cost-effective to select an appropriate depth for the disposal zone, giving due consideration to the containment of radionuclides and isolation from people. It is possible that the appropriate depth would lie in an intermediate depth range (e.g. 30 m to 300 m) between near-surface and deep geological disposal.

This section considers the various factors that need to be considered when choosing an appropriate depth.

Isolation

The sub-surface is intrinsically more isolated from the activities of people than the surface environment. Thus any disposal depth is likely to provide greater isolation from people than surface storage, and in general isolation will increase with depth.

It is generally appropriate to locate waste at depths where the geological environment is not affected by dynamic processes on the surface. In particular it is recommended that the disposal zone should be below the depth of seasonal temperature variations, and below the depth at which erosion could take place over the required isolation period.

The approach to quantifying the degree of isolation is to analyse stylised human intrusion scenarios [18]. These are inherently unpredictable as they necessarily involve the unpredictable actions of human beings. Thus the assessments cannot be viewed as predictions. Nevertheless this is a useful technique for thinking about the isolation of waste and how it might be improved.

Human activities are generally limited to about the first 30 m. If wastes are disposed of above this depth, it would generally be prudent to ensure that institutional controls are in place to deter possible intruders. These controls should be in place for a time commensurate with the period over which the radionuclides decay to insignificant levels. If this implies an unrealistic control period then the depth of the disposal zone should be increased to below 30 m.

If there are any requirements for waste retrievability following backfilling and sealing, then this would imply that the depth should be as close to the surface as possible, consistent with other constraints. This arises because of the increasing difficulty and cost of retrieval with depth. In contrast to retrievability, any requirements for security, to prevent intentional access to the waste, would favour disposal as deep as possible.

Containment

Radionuclide containment requirements can have important consequences for the choice of disposal depth. In essence, there needs to be a sufficiently long radionuclide travel time back to the biosphere for any radionuclides that might be released from the waste packages to allow time for decay.

Having a long groundwater flow path, low hydraulic conductivity and high sorption increases the radionuclide travel time. In choosing an appropriate depth, there is a potential trade-off between these three factors. For example, argillaceous rocks generally have both low hydraulic conductivity and high sorption for many radionuclides, and so might allow disposal at lesser depths than other rocks with less favourable characteristics. On the contrary, the disposal zone depth should be chosen so as to avoid regions of high hydraulic conductivity (aquifers).

5.3.6. Disposal facility operation

Prior to the operation of the facility, the operational controls, limitations and monitoring programmes need to be established and shown to be adequate. The regulatory process should ensure that these various elements of operational control and limitation are carried out and that an adequate programme of regulatory control is exercised over their implementation.

The operational phase of a borehole facility includes commissioning activities, waste reception and waste emplacement. In addition there can be a variety of engineering tasks including temporary storage or final conditioning of the waste. Operation of borehole facilities may be performed on a campaign basis or a continuous basis. Campaign operation involves the accumulation of waste in stores until there is sufficient to be disposed of in a new borehole. With continuous operation, packages are placed in the borehole as they arise.

In cases where a borehole or series of boreholes is operated on a campaign basis, safe and adequate storage arrangements will have to be available. This allows for a short term operational disposal period and would allow individual boreholes to be drilled, filled and sealed in one complete exercise, thus reducing the chances of boreholes degrading or being mismanaged between disposal operations.

The continuous operation of a borehole facility could require operational control to be exercised over the site by the operator for several years, together with control by the regulatory body. In both cases recognized technical and managerial principles need to be applied to achieve safe operations.

In particular, proper control needs to be maintained during commissioning and during the receipt and emplacement of waste in accordance with the established limits and conditions and the operating procedures and instructions. Appropriate emplacement of the waste packages is important for borehole disposal facilities taking into consideration the difficulty of retrieval of any improperly emplaced packages and of access to the different parts of the disposal facility. It is important to verify the techniques used for emplacement of waste and engineered barriers, for example in an inactive test facility. In particular it is necessary to ensure that:

- The possibility of dropping waste packages is limited;
- Waste packages are correctly backfilled;
- Waste packages are emplaced in the centre of the facility.

Emplacement of the waste packages will depend on the waste type and characteristics (activity, half-life, etc.) as well as on the characteristics of the engineered and natural barriers. It may be appropriate to place packages with high activity long lived sealed sources at the bottom part of the borehole facility and packages with low activity short lived radionuclides at the top in order to ensure long term safety, a higher level of isolation and limited consequences of human intrusion. The waste emplacement will also depend on the depth of the borehole facility and the disposal zone depth.

Last but by no means least, it is necessary for the operator to record relevant information for possible use in subsequent stages. Key information should be stored as required by the regulatory body. Such information will need to cover borehole location, identification of containers, location of waste packages, radionuclide content, the principal characteristics of the waste and the identities of its consignor and originator. Consideration needs to be given to the form of the records to ensure that information is available when needed without interruption or loss. The operator should ensure that only those wastes that comply with the waste acceptance requirements are accepted for disposal. The waste generators should make available to the operator of the facility, information to show that each consignment of waste has been or can be accepted as complying with the waste acceptance requirements. All information necessary for operational decisions on appropriate means of handling the waste in the facility should be included. The waste generator should provide with each waste consignment such documentation as is required by the operator or the regulatory body.

5.3.7. Disposal facility closure

Closure of a facility involves a series of systematic actions that are conducted after waste emplacement operations have been completed with the intention of providing a final configuration for the disposal system. Boreholes may be sealed and closed separately, or at the end of a disposal campaign. When all boreholes are closed, there is a need for site closure activities to be completed.

Sealing of boreholes requires sections above the disposal zone to be sealed in order to prevent shallow ground waters penetrating into the waste or the upward movement of pore-waters from the disposal zone. Standard borehole cementing and sealing approaches are likely to be appropriate, with the precise technique depending on the geology. Plugs would be required, within the host rock formation itself. In some geological environments, it may be appropriate to consider removing sections of borehole casing prior to or after the waste emplacement. This could allow a better bond of borehole backfill with the rock and could remove a potential leakage pathway to the surface, along degraded casing or poor grout to casing bonds.

It may be appropriate to remove part of the casing near the surface and install a plug beneath a final soil layer as a barrier to human, animal and plant intrusion and rainwater penetration into the borehole. The depth of the plug should be below the depth of seasonal temperature variations. The use of a heavy concrete plug that requires mechanical lifting equipment would be a further deterrent to human intrusion.

Closure of the upper parts of boreholes might aim to eliminate all traces of their existence. Alternatively, it may be designed to leave long term markers in place. Elimination of borehole traces means removing surface casing, concrete borehole collars, drilling and operational pads, etc. The upper five or ten metres of the holes might then be filled with local rock and soil representative of the near-surface formations penetrated.

The closure method should be optimized in the light of available materials and techniques, so as to enhance confidence in the safety case. The closure activities should be based on the post-closure safety assessment of the borehole facility and should identify the need for any controls intended for the post-closure phase. This could include radiological and other monitoring and surveillance and record keeping, and should identify the organization responsible for implementing these.

The closure design and implementation aim to minimize any need to maintain and repair the accessible parts of the facility during the institutional control period. The closure process should include the collation of all the information recorded during the previous phases that might be necessary for potential corrective actions in the future, or for reassessing the safety of the facility if it is warranted in the future. Some of the information will also be necessary to ensure that future generations know of the existence of the site.

5.3.8. Institutional controls

According to the IAEA safety requirements for near-surface disposal [16], *"long term safety shall be achieved through, amongst others, institutional controls"*. This implies that, generally, institutional control measures may be a factor in the implementation of a borehole disposal facility, especially to limit the probability of human intrusion. For borehole facilities, institutional controls are particularly relevant to the disposal of relatively short lived wastes within 30 m of the surface.

Institutional control is defined as any form of institutional activity, from oversight by international agencies and national governments, to very specific activities such as monitoring, surveillance, maintenance, record keeping and financial assurances. Active institutional controls include activities such as maintaining fences and guards at sites, monitoring, surveillance and performing any needed remedial work. Passive institutional controls include activities such as land use controls and the preservation of records.

The nature and maximum duration of controls as a means of ensuring compliance with safety criteria should be specified and justified with consideration given to the radioactive decay of the waste and its potential hazard, projected activities and historical experience of the retention of information. Reasonable assurance is needed that after the period of institutional control the radiological consequences of events that could affect the isolation and/or containment capability of the facility would be in compliance with the prescribed safety requirements and criteria.

Institutional control periods, often of the order of 100 to 300 years, are frequently part of the safety concept for many near-surface disposal facilities associated with nuclear power programmes. This concept implies that the site will remain under passive and/or active control so that access and land use can be restricted.

Institutional controls to prevent human intrusion are especially important for near-surface borehole facilities containing radionuclides with half-lives below about 30 years. If institutional controls can be relied upon for hundreds of years at such facilities, the radionuclides are likely to decay to harmless levels in isolation. This could be the case for sites with established security infrastructures, for example nuclear power facilities. However, for sites where there is little security infrastructure, the assumption of institutional control being maintained for such periods is less easy to justify.

Passive institutional controls can help to maintain knowledge of the facility location and characteristics within the institutions of society [28]. Such information should be retained for as long as possible to provide a basis for any future decisions concerning the site.

5.3.9. Monitoring and surveillance

Monitoring and surveillance are important for both public and technical reassurance. Monitoring programmes need to be designed and implemented so as not to reduce the overall level of long term safety. In general, monitoring will be required during each phase of disposal facility development:

- To provide reassurance to stakeholders including members of the public that the facility is performing as planned;
- To record or confirm the system description, to provide information for safety assessment and to provide baselines against which any changes can be assessed;
- To assure satisfactory conditions for the safe continuation of the current stage, including that doses to workers and members of public remain within design constraints and safety limits;

- To provide information to confirm the understanding which underlies a previous step or enhance the technical confidence to take the next step in the phased development of a borehole facility, or to identify reasons to delay or amend plans;
- To give an appropriate level of confirmation of the results of assessment calculations.

During the design or construction phase of a borehole facility, background radiological data should be collected as a pre-disposal benchmark, and used as reference levels. These data might include gamma radiation fields, radionuclide content of the dust, radon–thoron concentrations and radionuclide content of the soils, water and air on site. The results of pre-disposal monitoring will assist in building confidence in the safety and long term performance of the borehole facility and assist decisions for its future development.

Near-surface borehole disposal facilities should be subject to post-closure environmental monitoring of a similar nature to that proposed for near-surface disposal facilities. Facilities containing deeper boreholes could be monitored for potential releases through the nearby water bearing horizons, although releases of activity are not anticipated to occur, except possibly in the distant future.

The regulatory body should provide guidance in order to establish an environmental monitoring programme, including monitoring of releases and external exposure, and to assess the environmental impact of construction, operation, closure and post-closure activities. It should ensure by inspection on the site that the operations are carried out in accordance with established procedures as specified or referred to in the relevant licence or authorization and in existing regulations. The operator would normally carry out a monitoring programme and take necessary actions to ensure that the requirements established by national authorities are met. In addition, the regulators or another independent body may carry out an independent monitoring programme as a measure of public reassurance.

5.3.10. Quality assurance

An appropriate quality assurance programme needs to be applied to all activities, systems and components related to safety. A quality assurance programme will contribute to the confidence that the relevant safety requirements and criteria are met. The relevant activities, systems and components should be identified on the basis of results of systematic safety assessments of the various phases of the disposal facility. The level of attention granted to each aspect should be commensurate with its importance to safety. The programme should contain provision to identify, and assure compliance with, the recognized codes, regulations and standards relating to geological investigation, engineering and manufacture.

The programme should define the organizational structure for implementing the quality assurance activities and define the responsibilities and authorities of the various personnel and organizations involved in designing, implementing and auditing the quality assurance activities.

The quality assurance programme should provide for the production and retention of documentary evidence to illustrate that the necessary quality has been achieved, components supplied and utilized according to relevant specifications and the waste properly emplaced. It should also assure the collation of all the information recorded in the various stages, and the preservation of information that could be important to safety assessments of the facility in the future.

6. CONCLUSIONS

On the basis of the information reviewed in this report borehole disposal appears to be a promising option for the disposal of disused sealed sources. However, it remains for an "in depth" analysis of the technical feasibility and safety of this option to be carried out. These studies are currently being pursued by the IAEA and will be published in future technical documents. Moreover, the IAEA intends to develop formal safety guidance on this disposal option, as part of its Safety Standards Series of documents.

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ANNEX A
MANAGEMENT OF DISUSED SEALED SOURCES

Disused radiation sources need to be managed safely. The essential pre-disposal steps in setting up an effective system for assuring the safe management of disused radioactive sources at the national level are:

- To establish a national inventory of radioactive sources existing in the country (both those in use and disused sources);
- To locate and transport disused sources to national or regional facilities for long term storage (and eventual disposal of long lived sources);
- To characterize the sources and categorize them for storage (short lived radionuclides, with half-lives of weeks or months only) or interim storage pending disposal;
- To carry out any required conditioning and packaging of the sources for storage (with possibly further treatment for sources destined for disposal).

The development of national source inventories and the identification and location of disused sources is discussed in [A-1]. Neither of these steps is discussed further here. Conditioning of disused sources normally means the incorporation of the source in a shielded package for further handling, transport and storage. In some cases the source is placed in an over-pack for transport and storage. To date most attention has been paid to the conditioning of radium sources [A-2]. When there is uncertainty about the disposal of sources, little consideration tends to be given to disposal requirements when deciding about conditioning and packaging. As discussed below, this aspect would need to be considered if developing an integrated national or regional source management policy. In practice, transportation requirements are generally the main consideration at present. Transportation of all types of radioactive materials is discussed in [A-3] and is not discussed further in this report.

Collection, characterization, conditioning and storage are necessary precursors to disposal. Consequently, a national or regional strategy for source management should include the development of disused source handling and storage facilities.

Centralised storage facilities might contain sources that are long lived and awaiting disposal, or are being allowed to decay. Some medical sources contain radionuclides with half-lives of a few tens of days to several months (e.g. ^{125}I, ^{153}Gd, ^{192}Ir). A practical estimate of storage time for such sources would be a period of about 10–20 half-lives, or several years, depending on the initial source strength. Stores need to be well shielded, stable, dry structures with basic facilities for characterizing (monitoring) sources on receipt and managing health physics [A-4]. Characterization at the storage facility will allow a form of prioritization on sources that should make it possible to:

- Convert them in batches into conditioned form for long term storage (e.g. cemented into 200 L drums);
- Condition them in small packages designed for eventual disposal;
- Store individually shielded sources in their transport packaging, or deposit unshielded sources remotely into segregated, shielded vaults for later conditioning.

One design for the latter, aimed at minimum operator exposures, is to drop sources into small concrete vaults or cellars down a spiral tube, to minimize radiation shine. When not in use, the access is sealed with a shielded cover.

A detailed inventory of sources contained in the store and their locations needs to be kept, so that decayed sources (either singly, or conditioned in batches) can be identified, removed, checked and disposed of elsewhere as cleared materials, if required. Alternatively, for short lived sources only, vaults or cellars could be designed so that regions filled to capacity could be completed by injection of an inert matrix, such as cement, and sealed. This could form a disposal unit that remains in situ, under control, until the levels of radioactivity are low enough for the site of the store to be given clearance for unlimited use (some tens of years maximum).

In either case, allowance needs to be made for sources that may be leaking at the time of receipt. Consequently, containment of radionuclides needs to be assured by the conditioning matrix or the storage vaults themselves, rather than taking any credit for the source capsule materials. Some sources generate gases, which need to be monitored in the storage facility. Sealed radium sources can build up internal gas pressure from the production of radon gas that may leak over long periods in store.

Management of a store requires that sources be kept in categories, so that they can be put into batches for eventual disposal as cleared material, or to different types of facility. Different disposal solutions are appropriate for sources containing radionuclides with different half-lives. It is thus not good practice to condition or keep Category 3 sources (e.g. ^{226}Ra and ^{241}Am) with Category 2 sources (e.g. ^{60}Co, ^{137}Cs), or either of these categories with Category 1 sources (e.g. ^{125}I, ^{153}Gd, ^{192}Ir) if they cannot readily be separated without causing additional operator exposures.

Figure A-1 presents the typical ranges of source activity for various uses of sealed radioactive sources, and also indicates the magnitude of the problems caused when they become disused.

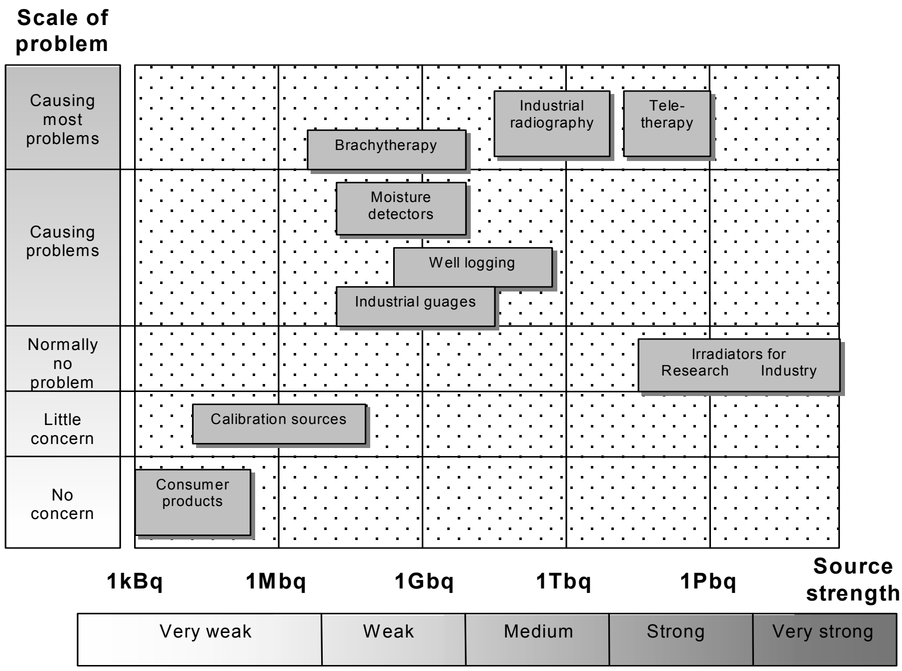

FIG. A-1. Activity ranges for some important radiation sources and the magnitude of the problems caused when they become disused [A-2].

Table A-1 presents estimates of the worldwide inventory of the main types of sealed radioactive sources.

Table A-2 presents examples of the types of disused sealed sources that might be considered for disposal in boreholes, and places them into three categories according to the radioactive half-life [A-5].

TABLE A-1. ESTIMATES OF THE WORLDWIDE INVENTORY OF THE MAIN TYPES OF SEALED RADIOACTIVE SOURCES IN 1998 (MODIFIED FROM [A-2])

Application	**Number of sources**	**Main radionuclides**	**Usual range or average activity of sources**
Medicine: Brachytherapy	100 000	^{137}Cs, ^{192}Ir, ^{226}Ra, ^{252}Cf, etc.	Tens to hundreds of MBq
Medicine: Teletherapy	2 600	^{60}Co ^{137}Cs	220 TBq 40 TBq
Medicine: Bone densitometry	Not available	^{241}Am, ^{153}Gd, ^{125}I	
Commercial irradiators	142	^{60}Co ^{137}Cs	40 PBq 400 PBq
Industrial radiography	25 000	^{60}Co, ^{137}Cs, ^{192}Ir, etc.	0.1 to some TBq
Industrial gauges	500 000	^{60}Co, ^{90}Sr, ^{137}Cs, ^{192}Ir, ^{238}Pu, ^{241}Am, etc.	0.1 to some tens of GBq
Well logging	Not available	$^{241}Am/Be$ ^{137}Cs	1 to 500 GBq 1 to 100 GBq

TABLE A-2. CATEGORIES OF DISUSED SEALED SOURCES THAT COULD BE CONSIDERED FOR BOREHOLE DISPOSAL (AFRA PROJECT)

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		Static eliminators
Gd-153	242 d		Bone dosimetry
Co-57	271.7 d	5.0E+05	Markers
Ru-106	1.0 a	5.0E+04	Manual brachytherapy

Radionuclide	Half-life	Maximum expected activity (MBq)	Application
Cf-252	2.6 a	5.0E+03	Calibration facilities
Pm-147	2.62 a	5.0E+05	Sources as standards in instruments
Co-60	5.3 a	5.0E+04	Sterilization and food preservation
Kr-85	10.8 a		Thickness gauge
H-3	12.3 a	5.0E+06	Tritium targets
Sr-90	29 a	5.0E+04	Thickness gauge
Cs-137	30.1 a	5.0E+05	Sterilization and food preservation
Category 3*	**Half-life >30 years**		
Pu-238	87.7 a	3.7E+03	Static electricity removal
Ni-63	100 a	5.0E+02	Electron capture detector
Am-241/Be	433 a	8.0E+05	Well logging
Ra-226	1600 a	3.7.E+03	Manual brachytherapy
C-14	5 700 a		
Cl-36	3.E+05 a	4.00	Sources as standards in instruments
I-129	1.6.E+7 a	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 safe long term disposal.

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ANNEX B
GENERAL OVERVIEW OF BOREHOLE FACILITIES IN MEMBER STATES

This annex presents some examples of borehole facilities that have been used in a number of countries for the storage and disposal of disused sealed sources and other radioactive waste over the last forty years. The majority of existing facilities are being used for storage rather than disposal purposes.

B.1. STORAGE OF LOW AND INTERMEDIATE LEVEL WASTE

Borehole facilities for the storage of low and intermediate level waste (LILW) are presently under development in the Russian Federation. The concept is based on fifty years of operational storage during which time the facility is monitored for its impacts on people and the environment. Following a satisfactory evaluation of the long term safety impacts, the large diameter boreholes would be backfilled and sealed transforming them into disposal facilities. Two borehole facilities of this kind have been constructed and put into operation at the MosRadon site (see Figure B-1).

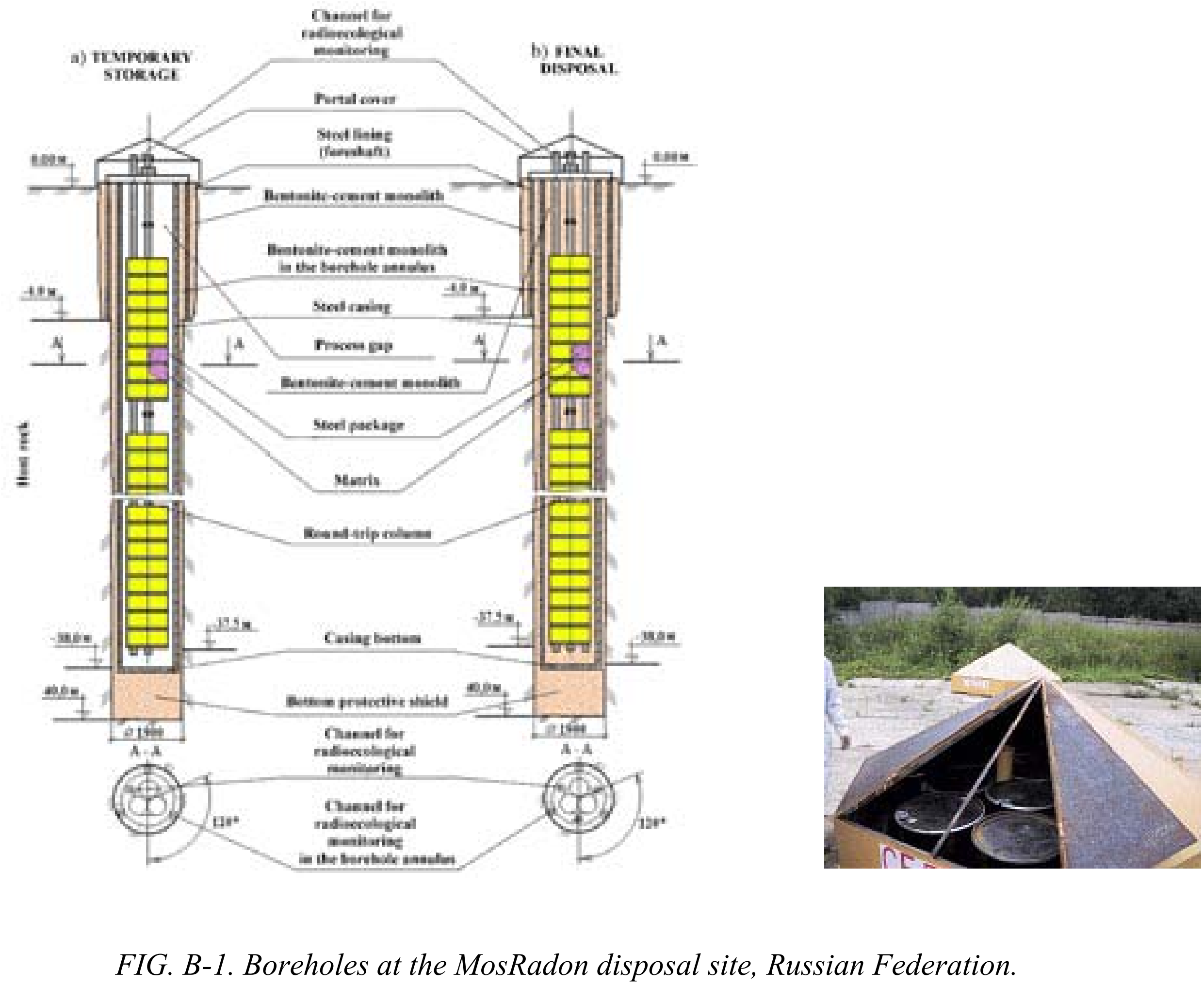

FIG. B-1. Boreholes at the MosRadon disposal site, Russian Federation.

Containment is provided by multiple barriers as follows:

- Waste matrix;
- Waste container;
- Backfill material surrounding waste containers within the borehole casing;
- Steel borehole casing;
- Bentonite-cement seals and upper and lower protective shields; and
- Natural barrier – the surrounding rock.

The boreholes have a depth of 40 m and have the main parameters as presented in Table B-1.

TABLE B-1. MAIN PARAMETERS OF BOREHOLE FACILITIES AT MOSRADON SITE

Depth	40 m
Borehole diameter	1.9 m
Depth of guide casing	3.0 m
Casing point	38.0 m
Number of casing sections	8
Thickness of casing walls Sections 1–3 Sections 3–5 Sections 5–8	 18mm 20 mm 22 mm
Inside casing diameter	1.5 m
Effective storage capacity	62.9 m^3
Waste volume for disposal	19.2 m^3
Thickness of upper protective shield	2.4 m

B.2. DISPOSAL

B.2.1. Current facilities for disused sealed sources

Over the past forty years the Radon system of regional specialised facilities for the management of institutional radioactive waste has been used in the Russian Federation, a number of the Newly Independent States and some countries in eastern Europe, including Hungary and Bulgaria. This system was established on a regional basis in the early 1960s based on the safety standards existing at that time. These facilities were sited close to large industrial and scientific centres that are currently close to populated areas.

The main types of disposal units at Radon facilities include vaults for solid radioactive waste, vaults for biological waste, and trenches and boreholes for disused sealed sources.

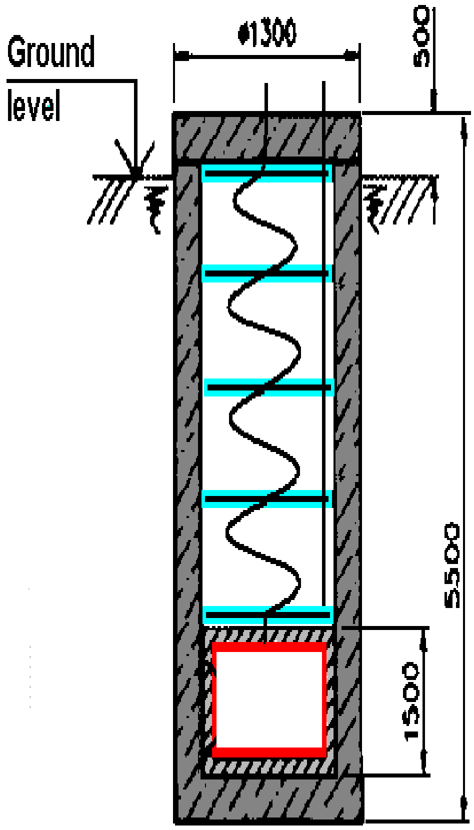

FIG. B-2. Near surface borehole for disposal (scale size in mm) of unconditioned sealed sources at a Radon type facility.

These facilities were designed, constructed and operated according to standard reference procedures. The disposal of unconditioned spent sealed sources takes place in specially designed boreholes. Spent sealed radiation sources with short lived radionuclides are usually disposed of at Radon facilities in near-surface boreholes (see Figure B.2), while sources with long lived radionuclides are stored in shielded containers pending a decision on their final disposal in deep geological facilities. For the disposal of the short lived spent sealed radiation sources, a standard design is available consisting of a stainless steel cylindrical vessel with a diameter of 200 mm and height of 1500 mm placed at 4 m depth in a steel-reinforced concrete borehole. The loading channel of the facility is in the form of a spiral tube. A carbon steel socket is located in the upper part of the facility that facilitates the loading of sources from the transport containers. A carbon steel lid closes the socket. Clay or a clay–cement mixture, which fills the initial construction hole, surrounds the concrete wall of the borehole facility. The reference design was used at most of the Radon facilities. However, different modifications have also been made at a number of sites (see Figure B-3).

The safety of most radon facilities is being re-assessed at present in order to evaluate if the facilities comply with modern safety requirements and criteria for waste disposal. However, as preliminary safety assessments have indicated that the main radiological hazard is due to the borehole facilities, some countries such as Hungary and the Russian Federation now consider the borehole facilities to be storage rather than disposal facilities.

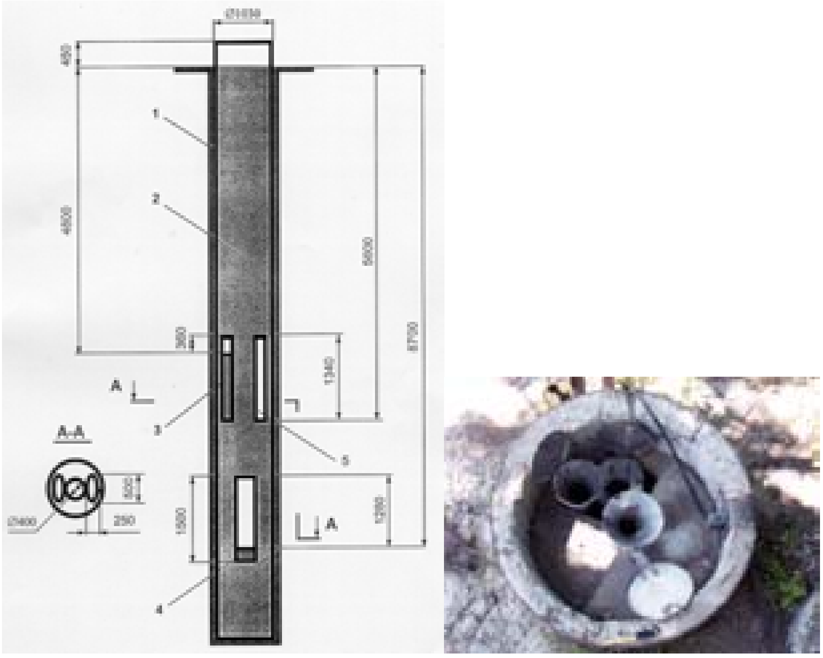

FIG. B-3. Borehole designed for the disposal of disused sealed sources in the Russian Federation (currently considered as storage facility; units [mm]).

An example of the disposal of disused sealed sources in a Radon type facility is the Püspökszilágy repository in Hungary situated about 40 km north of Budapest on the ridge of a hill near Püspökszilágy village. The waste has been disposed of in a number of different near-surface disposal units (trenches, vaults, boreholes) with engineered barriers. The disposal units are categorized into four classes (two types of vaults designated as ‘A’ and ‘C’ and borehole facilities for spent sealed radiation sources (SSRS) – B and D, see Table B-2).

TABLE B-2. STATUS OF THE DISPOSAL UNITS AT THE PÜSPÖKSZILÁGY REPOSITORY IN HUNGARY

Boreholes/lined tubes				
Type	Waste Category	Number	Diameter (mm)	Depth (mm)
B	SSRS	16	40	6000
	By-products of ^{60}Co source production	16	100	6000
D	SSRS ($t_{1/2} > 5$ years)	4	200	2000

Two types of boreholes initially designed for the disposal of disused sealed sources are currently being considered for the storage of high active disused sealed sources that await disposal in deep geological formations. These borehole disposal facilities are as follows.

Type B borehole facilities for disused sealed sources

The type B facilities consist of 16 boreholes with a diameter of 40 mm and 16 boreholes with a diameter of 100 mm. The boreholes are stainless steel lined and 6 m deep, located inside a concrete monolith structure. These facilities were designed to receive high activity (in the range of 100 GBq) ^{60}Co sources, but their storage capacity has been overestimated, so the boreholes are being used for the segregation of the sources. It was the initial practice for the sources to be placed in the boreholes and then grouted in position. This has now been reviewed and sources can now be placed for future retrieval.

Type D borehole facilities for disused sealed sources

The type D disposal system is made up of four boreholes with a diameter of 200 mm. The facilities are stainless steel lined down to 6 m depth (see Figure B-4). These units were designed for disposal and are utilized at present for storage of spent radiation sources with a half-life greater than 5 years.

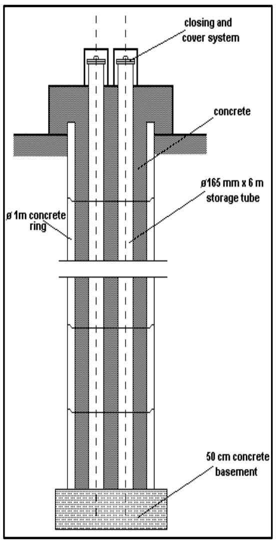

FIG. B-4. Facility D for disposal of disused sealed sources at the Püspökszilágy repository in Hungary.

An assessment of the total activity of the waste stored at Püspökszilágy was made at the end of 1997 and listed in the Table B.3 below. The total volume of solid and solidified waste is estimated at 4800 m^3.

TABLE B-3. SEALED SOURCES DISPOSED OF AT PÜSPÖKSZILÁGY REPOSITORY

Type of the Disposal unit	Activity (TBq)	No. of disposed Sources
“A” vault	103.82	17831
“B” small diameter boreholes	119.21	2057
“D” large diameter boreholes	8.44	4381
Total	231.47	24269

B.2.2. Planned facilities for the disposal of disused sealed sources

The Borehole Disposal of Sealed Sources (BOSS) concept has been under development as part of the IAEA Technical Co-operation AFRA project, specifically aimed at solving problems with the safe disposal of such sources in African countries (see Figure B-5).

Fundamental aspects considered in the design of the borehole facility are:

- the dimensions of the borehole should allow for the disposal of spent sources in suitable waste packages;
- the design of the borehole should take into consideration the operational requirements, e.g. waste emplacements should be able to take place as a matter of routine over the period during which it operates;

- the design should minimize the need for active maintenance after site closure and complement the natural characteristics of the site to reduce environmental impact; and
- human intrusion (advertent and inadvertent) should be difficult.

The BOSS disposal concept consists of a standard borehole (typical diameter 165 mm) drilled down to a depth of typically 100 m.

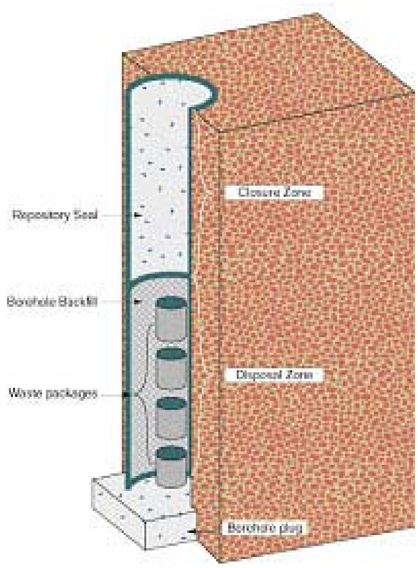

FIG. B-5. A schematic representation of the BOSS concept developed under the AFRA project.

Depending on the site-specific conditions, depths of less or more than 100 m could be acceptable. A 150 mm casing has been proposed to define the disposal volume. A bottom plug is provided to ensure that the disposal volume is dry during the operational period. It is envisaged that prior to closure the disposal area would be fenced off to limit access, and a temporary site office erected.

A reference design has been proposed that includes stainless steel container, a cement-based waste form and encapsulated sources. The waste package would be placed into wet concrete in the borehole. A specially formulated concrete would then be poured on and around the container. The next package would then be lowered into the hole and the process repeated (see Figure B-6). Packages would continue to be placed into the borehole until the waste acceptance limit or the cut-off depth is reached.

The rest of the borehole would be sealed with concrete. Specific provisions for retrievability have not yet been considered for disposal in boreholes. Whether the site should be marked or not requires consideration, taking into account the small "footprint" of a borehole. There is possibly merit in putting some sort of intrusion resistant cap at a shallow depth and then camouflaging the hole so that its presence is not obvious.

The need for institutional controls should be evaluated on the basis of the results of a comprehensive safety assessment. Preliminary safety assessments have been carried out using inventory data for the countries in the region and site data from the Vaalputs Shallow Land Repository site, and the Pelindaba site, both of which are in South Africa. The Vaalputs site example involved a shallow borehole of 45 m depth below surface in the unsaturated zone, while the Pelindaba example facility was 100 m deep in the saturated zone.

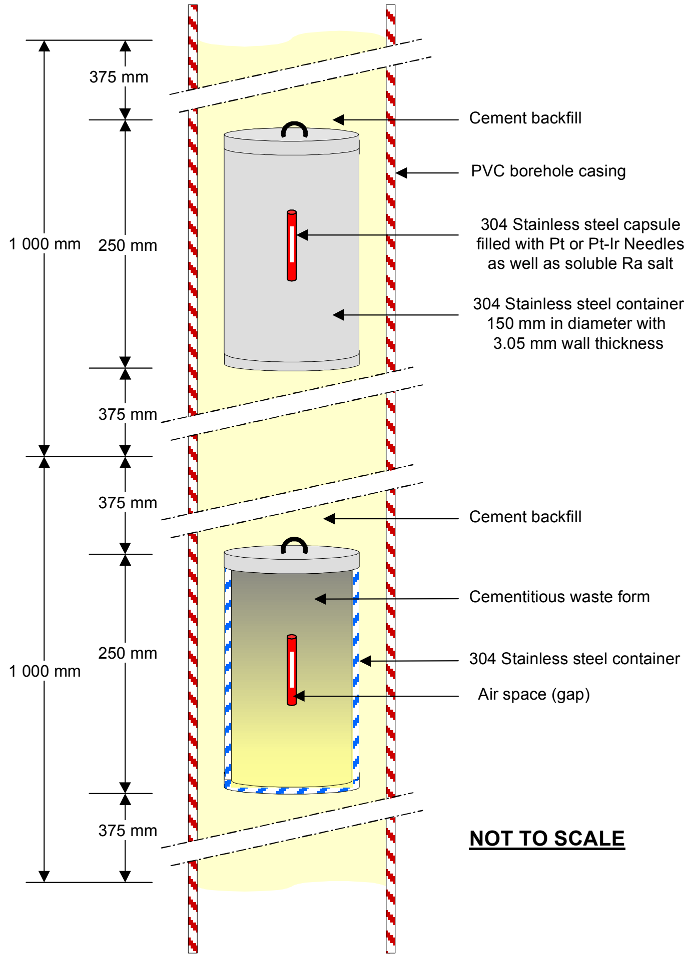

FIG. B-6. Borehole disposal of 200-litre drums of conditioned sealed sources.

B.2.3. Disposal of LLW in boreholes

Low level waste and chemical waste were disposed of in two boreholes and three trenches at the Mt Walton East site in Australia during two disposal campaigns in November–December 1992 and June–July 1994. The waste was placed into 60 litre drums filled with a cement mixture (Figure B-7).

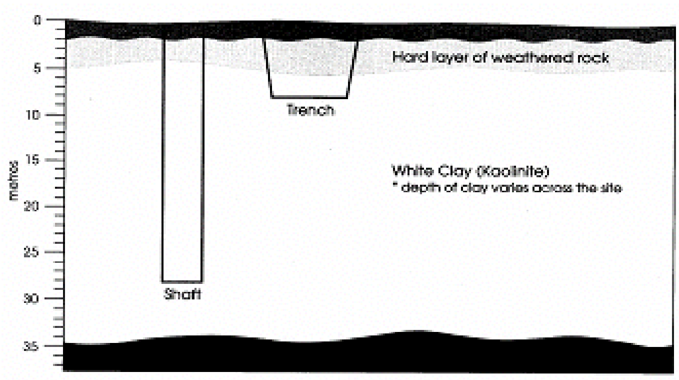

FIG. B-7. Disposal units (borehole and trenches) at the Mt Walton East site in Australia.

The drums were then placed in 200 litre steel drums, which were filled with concrete and disposed of in 2 m diameter boreholes 28 m deep with 3 drums per layer. The boreholes have a 0.5 m thick concrete base poured into the facility and specially designed steel pallets on which three 200 litre drums of waste are placed. Concrete was poured into the borehole facility after each pallet had been positioned. Once all the pallets were in place a final 0.5 m layer of concrete was poured and the remainder of the facility (the top 8 m) was backfilled with clay that had previously been excavated during the drilling of the borehole. The clay was compacted every meter and a prefabricated 200 mm concrete lid (5 t) was placed on the top and sealed with a silicon seal that was finally covered by compacted clay (see Figure B-8).

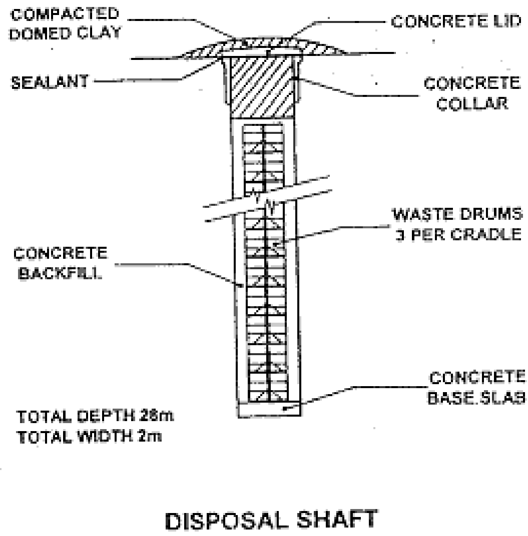

FIG. B-8. Borehole disposal facility at the Mt Walton East site in Western Australia.

The waste was placed in the two boreholes (5 m apart) and 66 drums were disposed of in the facility. The more active sources and long lived radionuclides were placed in the bottom of the facility. The waste accepted for disposal at the borehole facilities was that which exceeded the exemption limits (Radiation Safety Regulations of 1983) but excluded Ra-226 and uranium. A brief description of the waste inventory is presented in Table B-4.

B.2.4. Disposal of TRU in boreholes

Starting in 1984 and continuing through 1987, mixed transuranic waste (TRU), mostly in the form of classified accident debris from nuclear weapons, was placed in four large diameter Greater Confinement Disposal (GCD) boreholes along with high activity LLW principally containing ^{137}Cs at a depth of about 25 m at the Nevada Test Site in the USA [47]. The four boreholes have been backfilled and operationally closed.

TABLE B-4. SUMMARY OF THE INVENTORY OF RADIOACTIVE WASTE FOR THE BOREHOLE DISPOSAL FACILITY AT THE MT WALTON EAST SITE IN WESTERN AUSTRALIA

Radionuclide	Inventory [Bq]	Number of Items
Am-241	4.4.E+9	1362
Ba-133	1.2.E+8	5
C-14	7.4.E+5	1
Co-57	Negligible	1
Co-60	3.7E+9	36
Cs-137	3.2.E+11	78
Er-169	Negligible	1
Fe-55	Negligible	4
Gd-153	1.8E+9	1
H-3	3.7E+14	1010
Kr-85	5.9E+9	6
Na-22	1.0E+6	1
Ni-63	1.1.E+9	4
Pb-210	Negligible	1
Pm-147	1.0E+5	4
Sn-119	Negligible	3
Sr-90	1.3E+10	20
Th-232	1.1E+7	13

ANNEX C
ACTION LIST FOR DEVELOPMENT OF A BOREHOLE FACILITY

This annex presents practical guidance on activities that will need to be carried out and the decisions that need to be taken when developing a borehole disposal facility for disused sealed radiation sources and other limited amounts of waste. The following action list assumes that the regulatory framework is established and that waste acceptance criteria have been defined.

Activity 1: Collection, characterization and prioritization of sources and other waste;

Activity 2: Identification of an appropriate disposal site;

Activity 3: Characterization of disposal site environment;

Activity 4: Design of disposal facility;

Activity 5: Evaluation of safety and environmental impact assessment;

Activity 6: Conditioning & packaging of sources for disposal;

Activity 7: Operation and closure of disposal facility;

Activity 8: Post-closure.

Within each activity, specific tasks are marked as being either essential (E) or desirable (D). Some of the activities may involve the deployment of expertise outside that available within the country concerned. This is most likely to occur with respect to Activities 3 to 5 above.

ACTIVITY 1
COLLECTION, CHARACTERIZATION AND PRIORITIZATION OF SOURCES

Objective: To sort the waste according to their radionuclide contents and activity levels, and decide on their subsequent management.

Tasks

Task 1.1: Establish and maintain a national waste inventory and register of the status and properties of radioactive sources in the country. This should include both disused sources and those currently in use. (D)

Task 1.2: Locate and transport disused sources to a national or regional facility for long term storage and pre-disposal management. It would be desirable if this facility were located at the intended borehole disposal site. (E)

Task 1.3: Characterize the sources, based on labeling and accompanying technical documentation (supported, where possible, by gamma activity measurements) and categorize them as follows (E):

Category 1: For decay storage: those containing only radionuclides with half lives less than 100 days;

Category 2: For interim storage pending disposal in boreholes subject to institutional control until the activity has decayed to insignificant levels. Those containing mainly radionuclides with half-lives between 100 days and about 30 years;

Category 3: For interim storage pending disposal in boreholes at depths not requiring institutional control, e.g. geological facilities. Those containing any radionuclides with half-lives greater than about 30 years.

Task 1.4: Carry out any required packaging of the sources to make them stable for decay or interim storage. Further conditioning and packaging may be required for sources destined for disposal: see Task 6.1. Sources in the three categories should be kept separately at the management and storage facility, in a protected, dry, properly shielded and monitored environment. (D).

Task 1.5: Decide on the type of borehole disposal facility that will be required, based on the number of sources, their categories and their rate of accumulation. For a large number of sources and the expectation of regular future arisings, it may be decided to develop a disposal facility with an extended lifetime, with borehole disposal at a range of depths and where disposal takes place in campaigns. If the number of sources is small and contains a very small inventory of Category 3 radionuclides, and if only one campaign of disposal is envisaged, it may be decided to dispose of all sources in the last two categories in a near surface borehole. This will depend on the level of institutional control and site conditions and will need to be assessed on a case-by-case basis, in Stage 5 (E).

ACTIVITY 2
IDENTIFICATION OF AN APPROPRIATE DISPOSAL SITE

Objective: To find a site with suitable geological, hydrogeological and geomorphological properties for locating a borehole disposal facility that will provide adequate long term isolation and containment.

Tasks

Task 2.1: From an analysis of available geographical, geological and hydrogeological information for the country, identify areas with the following key characteristics (D):

- Either permanently unsaturated (predictable with confidence over the containment period of relevance) or low permeability saturated host rocks at an appropriate depth;
- Low hydraulic gradients in the host rocks and overlying formations;
- Lack of significant groundwater (aquifer) or mineral resources (including potential deep hydrocarbons);
- Low erosion rates and lack of susceptibility to flooding, occasional high rainfall events and land instability: for shallow boreholes, flat topography elevated above drainage or erosion levels may be the most appropriate;
- Lack of susceptibility of the surface or deep environment to major effects of climate change over the containment period of relevance (sea level fluctuations, river valley deepening);
- Local tectonic stability: not close to active fault lines or in areas prone to co-seismic level changes;
- Simple geological structure and hydrogeological system, avoiding areas of excessive geological complexity, which could be difficult to characterize and which may limit the degree of confidence in safety assessment results.

Task 2.2: Taking into account the availability of suitable access, land ownership and infrastructure, together with social and planning factors, identify potential sites lying within the areas that emerge from Task 2.1. Alternatively, it may be appropriate to consider these factors first, as they may identify realistically available sites that can then be compared with the characteristics of Task 2.1 to narrow down to a preferred site (E).

ACTIVITY 3
CHARACTERIZATION OF DISPOSAL SITE ENVIRONMENT

Objective: To obtain sufficient information on the site properties to establish the likely long term containment capacity by comparison with, and interpolation of, a range of generic safety assessment calculations.

Tasks

Task 3.1: Confirm by surface mapping that the geological structure and hydrology are relatively simple and reasonably well understood. The scale of mapping will be determined by the nature of the structures in the area. A geological, hydrogeological and hydrological model of the area should be developed from the mapping and from existing data, and used to identify target disposal zones at depth (E).

Task 3.2: Drill a pilot borehole at the preferred site, to a depth greater than the envisaged disposal zone. For disposal near to the surface, this should extend to the water table, if it is deeper than the disposal zone. For deeper boreholes, a pilot hole might typically extend 50–100 m deeper than the base of the disposal zone, to confirm that there are no features (e.g. underlying high pressure zones) that could affect performance. Exact borehole depths will depend on the interpretation of the geological and hydrogeological model. The objective of the pilot borehole is to gather data on rock hydraulic conductivities, hydraulic gradients, groundwater flow rates and groundwater chemistry. Optimally, the borehole should thus be designed to take core in (at least) the host formation, and should allow water sampling, ideally with flow-meter measurements, and standard geophysical logging as used in the hydrocarbons industry. Further near surface boreholes may be needed, distributed in the surrounding area, to determine the morphology of the water table and how it varies seasonally. Compilation of this information should give a clear indication of the nature of the groundwater regime and of the physical and chemical properties of the host formation (D).

ACTIVITY 4
DESIGN OF DISPOSAL FACILITY

Objective: To match the site characteristics and waste quantities and potential hazard to an appropriate borehole design.

Tasks

Task 4.1: Evaluate the constraints on facility and borehole design, namely:

- The number and types of sources to be disposed of;
- The period of time over which the sources will arise and the facility will need to be operational;
- Whether the facility is to be operated continuously, or on a campaign basis;

- The nature of the geological disposal environment;
- The local availability and capabilities of drilling and engineering technologies (e.g. feasible borehole diameters, casing technology, cementing technology);
- The availability of resources.

The main choice will be whether to dispose of sources in single campaigns and then seal boreholes, or keep boreholes open for a period, and fill them progressively, in several campaigns (E).

Task 4.2: Define an appropriate safety concept and associated design to match the constraints identified in Task 4.1. They should be adaptable to the range of circumstances likely to be encountered in most countries and situations (E).

ACTIVITY 5
EVALUATION OF SAFETY AND ENVIRONMENTAL IMPACT ASSESSMENT

Objective: To demonstrate with reasonable assurance that the disposal facility design, site and operation will provide an acceptable level of safety in order for the borehole facility to be licensed.

Tasks

Task 5.1: Perform safety assessment of the borehole facility taking into consideration the main features, events and processes that are relevant and important in evaluation of the long term behavior of the system considering both normal and disruptive events. Guidance on safety assessment and the development of a safety case that is consistent with relevant safety requirements is provided in the main body of this report. (E)

Task 5.2: Licensing is an important activity in the development and implementation of the borehole facility and should be undertaken in accordance with the national legislation. In some cases licences are granted for the whole lifecycle of the facility and in others they may be required for each stage of the facility development – siting, design, construction, operation, closure and post-closure. Further guidance on licensing is provided in Section 4.2.2 in the main text of this report. (E)

Task 5.3: Performance of environmental impact assessment is required in some countries with operators being required to demonstrate that development of a borehole facility will not have an unacceptable level of impact on the environment. In most cases these assessments are related to evaluation of non-radiological impacts from the facility during its development, operation and post-closure phases such as transport to and from the site and construction work associated with the facility. (D)

ACTIVITY 6
CONDITIONING AND PACKAGING OF SOURCES FOR DISPOSAL

Objective: Production of waste packages suitable for emplacement in the borehole.

Tasks

Task 6.1: Sources should be removed from interim storage and placed singly or in batches into packages suitable for movement from the store and emplacement in the borehole facility. For example, this may involve embedding them in a cement or lead matrix inside a disposal container. Appropriate designs for such containers will depend on the overall facility design and the size and nature of the sources. An objective should be to minimize the amount of handling and manipulation required to place them in packages. A detailed record should be kept of the sources placed in each package (E).

ACTIVITY 7
OPERATION AND CLOSURE OF DISPOSAL FACILITY

Objective: Emplacement of sources into boreholes and sealing the facilities, leaving the site in a state such that it can either be completely vacated or kept under control.

Tasks

Task 7.1: Waste package emplacement could be expected to proceed in campaigns, filling either a complete borehole or a section of a borehole before either completely sealing, or sealing off a filled length of hole. Sealing of boreholes requires long sections above the disposal zone to be sealed up to prevent shallow ground waters penetrating into the waste or the upward movement of pore-waters from the disposal zone. Standard borehole cementing and sealing approaches are likely to be appropriate. Plugs several metres long would be required, within the host rock formation itself. In some geological environments, it may be appropriate to consider removing borehole casing prior to waste emplacement, to allow a better bond of borehole backfill grout with the rock and to remove a potential leakage pathway to the surface (along degraded casing or poor grout to casing bonds) (E).

Task 7.2: Closure of the site. Closure of the upper parts of boreholes might aim to eliminate all traces of their existence or, conversely, may be designed to leave long term markers in place. In either case, proper facility design and waste emplacement should allow the land to be returned to normal use after closure of the borehole. Elimination of borehole traces means removing surface casing, concrete borehole collars, drilling and operational pads, etc. The upper five or ten metres of the holes might then be filled with local rock and soil representative of the shallow formations penetrated (D).

Task 7.3: Detailed records of disposals, including the exact location of the site, the position, depth and design of boreholes, the packages emplaced and their contents, and the sealing method used should be lodged with national authorities, as well as with any local authorities responsible for land use planning (E).

ACTIVITY 8
POST-CLOSURE

Objective: To ensure control over the site in order to minimize the possibilities for human intrusion.

Tasks

Task 8.1: Perform active or passive control and carry out monitoring for a period of time justified based on the results of the safety assessment, and existing infrastructure (D).

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