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IAEA Safety Standards

for protecting people and the environment

Borehole Disposal Facilities for Radioactive Waste

Specific Safety Guide

No. SSG-1

IAEA

International Atomic Energy Agency

IAEA SAFETY RELATED PUBLICATIONS

IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish or adopt standards of safety for protection of health and minimization of danger to life and property, and to provide for the application of these standards.

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The site provides the texts in English of published and draft safety standards. The texts of safety standards issued in Arabic, Chinese, French, Russian and Spanish, the IAEA Safety Glossary and a status report for safety standards under development are also available. For further information, please contact the IAEA at PO Box 100, 1400 Vienna, Austria.

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BOREHOLE DISPOSAL FACILITIES FOR RADIOACTIVE WASTE

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA SAFETY STANDARDS SERIES No. SSG-1

BOREHOLE DISPOSAL FACILITIES FOR RADIOACTIVE WASTE

SPECIFIC SAFETY GUIDE

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FOREWORD

The IAEA's Statute authorizes the Agency to establish safety standards to protect health and minimize danger to life and property — standards which the IAEA must use in its own operations, and which a State can apply by means of its regulatory provisions for nuclear and radiation safety. A comprehensive body of safety standards under regular review, together with the IAEA's assistance in their application, has become a key element in a global safety regime.

In the mid-1990s, a major overhaul of the IAEA's safety standards programme was initiated, with a revised oversight committee structure and a systematic approach to updating the entire corpus of standards. The new standards that have resulted are of a high calibre and reflect best practices in Member States. With the assistance of the Commission on Safety Standards, the IAEA is working to promote the global acceptance and use of its safety standards.

Safety standards are only effective, however, if they are properly applied in practice. The IAEA's safety services — which range in scope from engineering safety, operational safety, and radiation, transport and waste safety to regulatory matters and safety culture in organizations — assist Member States in applying the standards and appraise their effectiveness. These safety services enable valuable insights to be shared and I continue to urge all Member States to make use of them.

Regulating nuclear and radiation safety is a national responsibility, and many Member States have decided to adopt the IAEA's safety standards for use in their national regulations. For the contracting parties to the various international safety conventions, IAEA standards provide a consistent, reliable means of ensuring the effective fulfilment of obligations under the conventions. The standards are also applied by designers, manufacturers and operators around the world to enhance nuclear and radiation safety in power generation, medicine, industry, agriculture, research and education.

The IAEA takes seriously the enduring challenge for users and regulators everywhere: that of ensuring a high level of safety in the use of nuclear materials and radiation sources around the world. Their continuing utilization for the benefit of humankind must be managed in a safe manner, and the IAEA safety standards are designed to facilitate the achievement of that goal.

THE IAEA SAFETY STANDARDS

BACKGROUND

Radioactivity is a natural phenomenon and natural sources of radiation are features of the environment. Radiation and radioactive substances have many beneficial applications, ranging from power generation to uses in medicine, industry and agriculture. The radiation risks to workers and the public and to the environment that may arise from these applications have to be assessed and, if necessary, controlled.

Activities such as the medical uses of radiation, the operation of nuclear installations, the production, transport and use of radioactive material, and the management of radioactive waste must therefore be subject to standards of safety.

Regulating safety is a national responsibility. However, radiation risks may transcend national borders, and international cooperation serves to promote and enhance safety globally by exchanging experience and by improving capabilities to control hazards, to prevent accidents, to respond to emergencies and to mitigate any harmful consequences.

States have an obligation of diligence and duty of care, and are expected to fulfil their national and international undertakings and obligations.

International safety standards provide support for States in meeting their obligations under general principles of international law, such as those relating to environmental protection. International safety standards also promote and assure confidence in safety and facilitate international commerce and trade.

A global nuclear safety regime is in place and is being continuously improved. IAEA safety standards, which support the implementation of binding international instruments and national safety infrastructures, are a cornerstone of this global regime. The IAEA safety standards constitute a useful tool for contracting parties to assess their performance under these international conventions.

THE IAEA SAFETY STANDARDS

The status of the IAEA safety standards derives from the IAEA's Statute, which authorizes the IAEA to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property, and to provide for their application.

With a view to ensuring the protection of people and the environment from harmful effects of ionizing radiation, the IAEA safety standards establish fundamental safety principles, requirements and measures to control the radiation exposure of people and the release of radioactive material to the environment, to restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation, and to mitigate the consequences of such events if they were to occur. The standards apply to facilities and activities that give rise to radiation risks, including nuclear installations, the use of radiation and radioactive sources, the transport of radioactive material and the management of radioactive waste.

Safety measures and security measures[1] have in common the aim of protecting human life and health and the environment. Safety measures and security measures must be designed and implemented in an integrated manner so that security measures do not compromise safety and safety measures do not compromise security.

The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. They are issued in the IAEA Safety Standards Series, which has three categories (see Fig. 1).

Safety Fundamentals

Safety Fundamentals present the fundamental safety objective and principles of protection and safety, and provide the basis for the safety requirements.

Safety Requirements

An integrated and consistent set of Safety Requirements establishes the requirements that must be met to ensure the protection of people and the environment, both now and in the future. The requirements are governed by the objective and principles of the Safety Fundamentals. If the requirements are not met, measures must be taken to reach or restore the required level of safety. The format and style of the requirements facilitate their use for the establishment, in a harmonized manner, of a national regulatory framework. The safety requirements use ‘shall’ statements together with statements of

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[1] See also publications issued in the IAEA Nuclear Security Series.

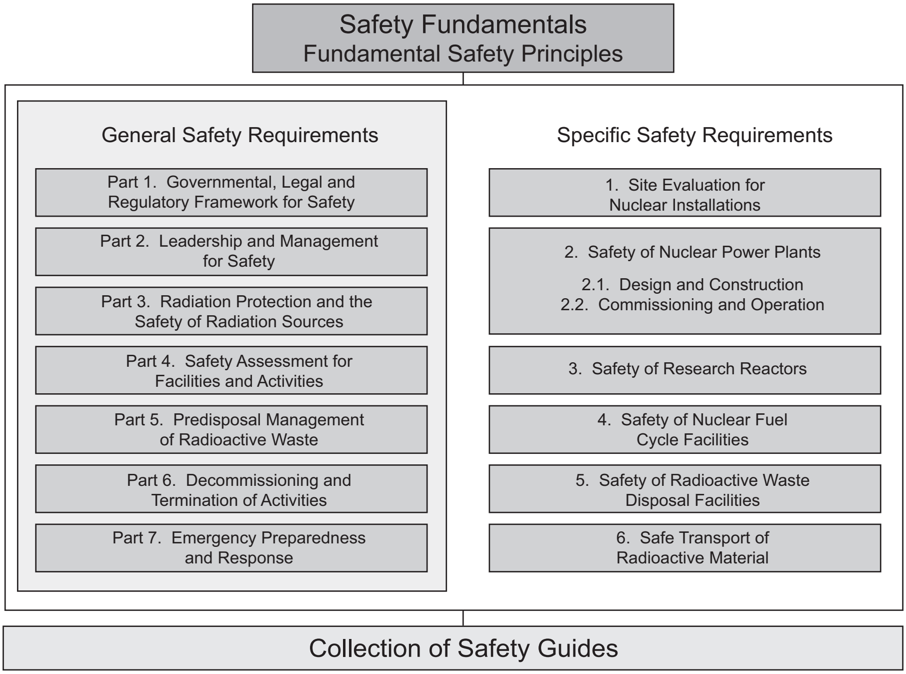

FIG. 1. The long term structure of the IAEA Safety Standards Series.

associated conditions to be met. Many requirements are not addressed to a specific party, the implication being that the appropriate parties are responsible for fulfilling them.

Safety Guides

Safety Guides provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus that it is necessary to take the measures recommended (or equivalent alternative measures). The Safety Guides present international good practices, and increasingly they reflect best practices, to help users striving to achieve high levels of safety. The recommendations provided in Safety Guides are expressed as 'should' statements.

APPLICATION OF THE IAEA SAFETY STANDARDS

The principal users of safety standards in IAEA Member States are regulatory bodies and other relevant national authorities. The IAEA safety standards are also used by co-sponsoring organizations and by many organizations that design, construct and operate nuclear facilities, as well as organizations involved in the use of radiation and radioactive sources.

The IAEA safety standards are applicable, as relevant, throughout the entire lifetime of all facilities and activities — existing and new — utilized for peaceful purposes and to protective actions to reduce existing radiation risks. They can be used by States as a reference for their national regulations in respect of facilities and activities.

The IAEA's Statute makes the safety standards binding on the IAEA in relation to its own operations and also on States in relation to IAEA assisted operations.

The IAEA safety standards also form the basis for the IAEA's safety review services, and they are used by the IAEA in support of competence building, including the development of educational curricula and training courses.

International conventions contain requirements similar to those in the IAEA safety standards and make them binding on contracting parties. The IAEA safety standards, supplemented by international conventions, industry standards and detailed national requirements, establish a consistent basis for protecting people and the environment. There will also be some special aspects of safety that need to be assessed at the national level. For example, many of the IAEA safety standards, in particular those addressing aspects of safety in planning or design, are intended to apply primarily to new facilities and activities. The requirements established in the IAEA safety standards might not be fully met at some existing facilities that were built to earlier standards. The way in which IAEA safety standards are to be applied to such facilities is a decision for individual States.

The scientific considerations underlying the IAEA safety standards provide an objective basis for decisions concerning safety; however, decision makers must also make informed judgements and must determine how best to balance the benefits of an action or an activity against the associated radiation risks and any other detrimental impacts to which it gives rise.

DEVELOPMENT PROCESS FOR THE IAEA SAFETY STANDARDS

The preparation and review of the safety standards involves the IAEA Secretariat and four safety standards committees, for nuclear safety (NUSSC), radiation safety (RASSC), the safety of radioactive waste (WASSC) and the safe transport of radioactive material (TRANSSC), and a Commission on

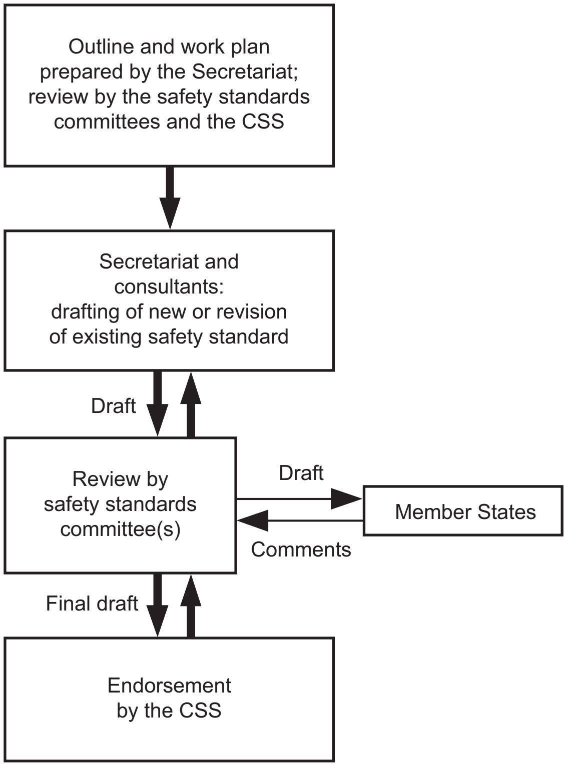

FIG. 2. The process for developing a new safety standard or revising an existing standard.

Safety Standards (CSS) which oversees the IAEA safety standards programme (see Fig. 2).

All IAEA Member States may nominate experts for the safety standards committees and may provide comments on draft standards. The membership of the Commission on Safety Standards is appointed by the Director General and includes senior governmental officials having responsibility for establishing national standards.

A management system has been established for the processes of planning, developing, reviewing, revising and establishing the IAEA safety standards. It articulates the mandate of the IAEA, the vision for the future application of the safety standards, policies and strategies, and corresponding functions and responsibilities.

INTERACTION WITH OTHER INTERNATIONAL ORGANIZATIONS

The findings of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the recommendations of international expert bodies, notably the International Commission on Radiological Protection (ICRP), are taken into account in developing the IAEA safety standards. Some safety standards are developed in cooperation with other bodies in the United Nations system or other specialized agencies, including the Food and Agriculture Organization of the United Nations, the United Nations Environment Programme, the International Labour Organization, the OECD Nuclear Energy Agency, the Pan American Health Organization and the World Health Organization.

INTERPRETATION OF THE TEXT

Safety related terms are to be understood as defined in the IAEA Safety Glossary (see http://www-ns.iaea.org/standards/safety-glossary.htm). Otherwise, words are used with the spellings and meanings assigned to them in the latest edition of The Concise Oxford Dictionary. For Safety Guides, the English version of the text is the authoritative version.

The background and context of each standard in the IAEA Safety Standards Series and its objective, scope and structure are explained in Section 1, Introduction, of each publication.

Material for which there is no appropriate place in the body text (e.g. material that is subsidiary to or separate from the body text, is included in support of statements in the body text, or describes methods of calculation, procedures or limits and conditions) may be presented in appendices or annexes.

An appendix, if included, is considered to form an integral part of the safety standard. Material in an appendix has the same status as the body text, and the IAEA assumes authorship of it. Annexes and footnotes to the main text, if included, are used to provide practical examples or additional information or explanation. Annexes and footnotes are not integral parts of the main text. Annex material published by the IAEA is not necessarily issued under its authorship; material under other authorship may be presented in annexes to the safety standards. Extraneous material presented in annexes is excerpted and adapted as necessary to be generally useful.

CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. The use of radioactive material in nuclear research and in industrial, medical and other applications has led to the generation of small but significant volumes of radioactive waste. Some of this waste (e.g. disused radioactive sources from industrial and medical uses) is intensely radioactive. Consequently, many States now have various types of radioactive waste, all of which need to be managed and disposed of robustly and safely. The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [1] places an obligation on Contracting Parties to control and manage such radioactive waste safely.

1.2. When the activity in waste is relatively low and half-lives are less than about 30 a, near surface disposal will often be suitable. Some waste, however, is too radioactive and too long lived for near surface disposal. Such waste requires higher levels of containment and isolation than can be provided by near surface facilities, implying the need for disposal at greater depths. In States where there is a significant nuclear industry, possibilities for deep disposal may exist or, more often, may be planned. Such States are relatively few in number, however. More often, States have radioactive waste, but lack the possibility of safe disposal for such waste types, or even the prospect of such. For example, radioactive sources used in industry and medicine may be high energy photon emitters that require heavily shielded containers for their safe use, transport and storage. At the end of their useful lifetime, it is possible in some cases to return these sources to their manufacturer for recycling. In many cases though, this is not possible and even though they may be ‘spent’ sources (i.e. no longer radioactive enough for their intended use), they still present a significant hazard. This is evident from a number of incidents and accidents, including fatalities, that have arisen from their misuse [2].

1.3. Where the radionuclides in the waste have relatively short half-lives (e.g. ^{60}Co, half-life 5.3 a) and an activity of less than a few tens of MBq, it may be reasonable to assume that they can safely be placed in a facility, such as a near surface disposal facility, for the ten to twenty half-lives necessary to allow the radioactivity to decay to safe levels. For longer lived and higher activity sources and other waste, however, storage is merely an interim solution that is acceptable only as long as the search continues for a long term solution. One potential long term solution for such waste is deep disposal in an engineered, cavern type repository.

1.4. An alternative solution is disposal in specially engineered and purpose drilled boreholes (loosely referred to as 'borehole disposal' [3]), which offers the prospect of economic disposal on a small scale while, at the same time, meeting all the safety requirements. The comparative ease of borehole construction and site characterization may make this method of disposal particularly suitable for States, or regional groupings of States, that have limited amounts of waste. Disposal in borehole disposal facilities is seen as having particular value for the disposal of disused sealed radioactive sources. As a general rule, however, disused sealed radioactive sources containing materials that may pose hazards to inadvertent intruders or that may be used in radioactive dispersal devices should not be placed in near surface disposal facilities.

1.5. Borehole type facilities have been used in the past in a number of States for the storage and disposal of radioactive waste; all of them are located on existing waste repository sites [3]. In the Russian Federation, for example, there has been more than 40 a of experience with borehole disposal facilities of up to 15 m in depth [4] and new facilities are being planned there [5]. Also, the Greater Confinement Test facility in Nevada, United States of America, has already been used to dispose of waste in boreholes 10 m deep by 3 m in diameter [6]. Examples such as these are considered in this Safety Guide with a view to identifying good practices. There are, however, some cases of questionable practice: concerns have been expressed, for example, over the degree of isolation provided by certain existing borehole disposal facilities in terms of their siting and depth, the reliability and efficiency of the isolation barriers and the adequacy of the associated safety assessments. These concerns highlight the need for guidance on the evaluation of the safety of existing facilities so that decisions can be taken on the necessity for remedial measures.

OBJECTIVE

1.6. The objective of this Safety Guide is to provide guidance on the design, construction, operation and closure of borehole disposal facilities for the disposal of radioactive waste in accordance with the relevant safety requirements [7–9]. The guidance can also be used as a basis for reassessing the safety of existing facilities. Compliance with the safety requirements should provide protection for people and the environment from exposure to ionizing radiation. The safety objectives and associated criteria for borehole disposal are no less stringent than for geological disposal or near surface disposal. However, because of the relatively small quantities (in terms of both volume and activity) of waste, considerably less effort would be required to meet these objectives and the associated criteria — and to demonstrate that they will be or have been met — than would be the case for the larger scale practices.

1.7. As a practice, the disposal of radioactive waste in borehole disposal facilities falls between the two well-established options of disposal in near surface facilities and disposal in geological facilities. This Safety Guide, therefore, complements both the Safety Guide on near surface disposal [10] and the Safety Guide on geological disposal [11].

1.8. The Safety Guide is intended to support a practical and systematic approach to decision making for borehole disposal such as would be required within the framework of a management system providing for the necessary level of quality (see Appendix VI).

SCOPE

1.9. Existing or proposed borehole disposal facilities exhibit a wide range of diameters and depths, including shafts and small diameter boreholes sunk to various depths. While the present Safety Guide is relevant for all these possibilities, its main focus is on boreholes having a diameter of no more than a few hundred millimetres and a depth beyond a few tens of metres and up to a few hundred metres (i.e. the depth range between near surface disposal and geological disposal).

1.10. While borehole disposal facilities may also be suitable for other types of waste, this Safety Guide concentrates on disused sealed sources and small volumes of low and intermediate level wastes. Throughout this Safety Guide, the term ‘disused sealed sources’ refers to sealed sources that, for whatever reason, have fallen out of use and have been categorized as waste. The typical radionuclides to be found in disused sealed sources are listed in Table 1. It is envisaged that the type of radionuclides and/or waste for which borehole disposal is most likely to be suitable would need to be:

(a) Too long lived for decay storage (e.g. a half-life greater than a few years);
(b) Too long lived and/or too radioactive to be placed in a simple near surface facility;
(c) Small volume waste for which no other disposal facility is available.

TABLE 1. TYPICAL RADIONUCLIDES PRESENT IN DISUSED SEALED SOURCES

Radionuclide	Half-life	Maximum expected activity (MBq)	Application
	<100 d		
Au-198	2.7 d	1.5E3	Manual brachytherapy
Y-90	2.7 d	5E2	Manual brachytherapy
I-131	8.0 d	1.5E3	Manual brachytherapy
P-32	14.3 d	2E2	Vascular brachytherapy
Pd-103	17.0 d	1.5E3	Manual brachytherapy
Sr-89	50.5 d	1.5E2	Vascular brachytherapy
I-125	60.0 d	1E4	Bone dosimetry
Ir-192	74.0 d	5E6	Industrial radiography
	100 d to ≤30 a		
Po-210	138.0 d		Static electricity eliminators
Gd-153	242.0 d		Bone dosimetry
Co-57	271.7 d	5E5	Markers
Ru-106	1.0 a	5E4	Manual brachytherapy
Cf-252	2.6 a	5E3	Calibration facilities
Pm-147	2.6 a	5E5	Sources as standards in instruments
Co-60	5.3 a	5E4	Sterilization and food preservation
Kr-85	10.8 a		Thickness gauges
H-3	12.3 a	5E6	Tritium targets
Sr-90	29.0 a	5E4	Thickness gauges
Cs-137	30.1 a	5E5	Sterilization and food preservation

TABLE 1. TYPICAL RADIONUCLIDES PRESENT IN DISUSED SEALED SOURCES (cont.)

Radionuclide	Half-life	Maximum expected activity (MBq)	Application
	>30 a		
Pu-238	87.7 a	3.7E3	Static electricity eliminators
Ni-63	100 a	5E2	Electron capture detectors
Am-241/Be	433 a	8E5	Well logging, fire detection
Ra-226	1600 a	3.7E3	Manual brachytherapy
C-14	5700 a		
Cl-36	3E5 a	4.00	Sources as standards in instruments
I-129	1.6E7 a	4.00	Sources as standards in instruments

1.11. Consideration is given to operational safety, the security of the waste and the achievement of post-closure safety. It is recognized that, while radiological safety is of paramount importance, it is only part of a broader context that includes planning, financial, economic and social issues, and non-radiological safety. These other issues are not specifically covered in this Safety Guide.

1.12. This Safety Guide is intended for those persons whose prime interest is in the regulation and implementation of the safe disposal of radioactive waste.

STRUCTURE

1.13. In this Safety Guide, the background to, concept of, and protection and safety objectives for, borehole disposal are set out in Sections 1–3. Recommendations on how to apply the relevant safety requirements to borehole disposal are provided in Sections 4 and 5. Section 6 describes the application of the safety strategy to existing borehole disposal facilities.

2. BOREHOLE DISPOSAL AND THE SAFETY OF RADIOACTIVE WASTE MANAGEMENT

BOREHOLE DISPOSAL CONCEPT

2.1. The borehole disposal concept (shown schematically in Fig. 1) entails the emplacement of disused sealed radioactive sources and small volumes of low and intermediate level wastes in an engineered facility bored or drilled and operated directly from the surface. In this Safety Guide, borehole disposal is envisaged mainly as a small scale activity that can be carried out without a large programme of scientific and site investigation.

2.2. In this Safety Guide, a depth of 30 m is used to differentiate between near surface disposal and disposal at intermediate and greater depths. This depth is widely accepted as the lower level of the ‘normal residential intrusion zone’ (i.e. a depth beyond which human intrusion is limited to drilling and significant excavation activities, such as tunnelling, quarrying and mining) [12]. In applying this distinction, the key parameter is not the maximum depth of the borehole but, rather, the minimum depth at which waste is located within the

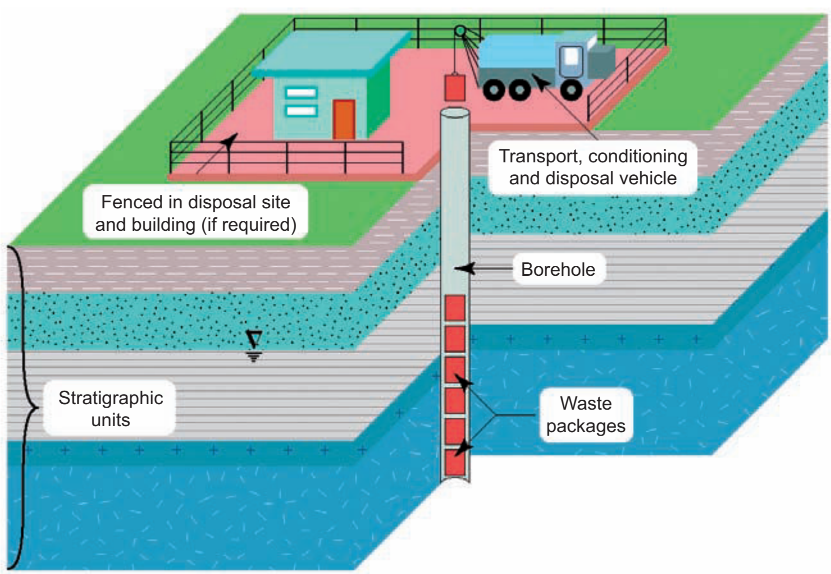

FIG. 1. Schematic layout of a borehole disposal facility.

borehole. So, even if a borehole is several hundred metres deep, if the column of waste within it extends to less than 30 m below the surface, the borehole will be considered to be a near surface disposal facility. If all the waste is located at a depth that exceeds 30 m below the surface, it will be referred to as an intermediate depth disposal facility.

2.3. From a safety perspective, borehole disposal is not conceptually different from either near surface disposal or geological disposal of radioactive waste. Indeed, because the range of depths accessed by borehole disposal approaches the depths normally associated with both near surface disposal and geological disposal, consideration is given to elements of both. As for near surface disposal and geological disposal, a combination of natural barriers and engineered barriers contribute to safety for borehole disposal. In combination, these barriers are designed to contain radioactive material until it has decayed to insignificant levels, and to provide sufficient isolation and containment to ensure an adequate level of protection for people and the environment.

APPLYING THE SAFETY PRINCIPLES IN RADIOACTIVE WASTE MANAGEMENT

2.4. The safety principles applicable to all facilities and activities, including waste disposal activities, are established in the Fundamental Safety Principles [13]. Because borehole disposal facilities are used to dispose of waste at a range of depths, from depths associated with near surface disposal to depths approaching those associated with geological disposal, and because of the nature of the waste intended for disposal, guidance needs to be provided on how the safety requirements for both geological disposal [8] and near surface disposal [9] can be met for these facilities.

2.5. The graded application of the safety requirements for near surface disposal and geological disposal to borehole disposal will ensure an adequate level of safety. In all cases, reasonable assurance of safety should be demonstrated to the regulatory body and to other stakeholders. However, the level of effort required to comply with these safety requirements for a facility with a relatively small inventory of radionuclides will generally be significantly less than for large scale repositories in terms of safety assessment, site characterization and facility construction, operation and closure. The use of generic safety assessment, which could assist in the assessment of particular sites, to facilitate safety assessment for borehole disposal facilities is discussed in paras 5.7–5.9.

3. BOREHOLE DISPOSAL AND THE PROTECTION OF HUMAN HEALTH AND THE ENVIRONMENT

RADIATION PROTECTION DURING THE OPERATIONAL PERIOD

3.1. The objective for radiation protection during the operational period of a borehole disposal facility and the related safety criteria are the same as for any licensed nuclear facility and are as required by the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [7] (see Box 1). In radiation protection terms, the source is under control, releases can be verified, exposures can be controlled and actions can be taken if needed. Optimization of radiation protection is the primary goal (application of principle 5 of Ref. [13]). See also under the heading ‘Objective’ in Box 2.

3.2. Only very minor releases of radionuclides (such as small amounts of gaseous radionuclides) may be expected during pre-disposal activities and during the operation of a borehole disposal facility. The design should be such that, even in the event of an accident involving the breach of a waste package, releases are not likely to have any impact outside the facility. Relevant considerations should include the packaging, the waste form, the radionuclide content of the waste and control of contamination on packages and equipment.

3.3. A radiological protection programme should be in place during the operational period. This should ensure that doses to workers are controlled and that the requirements for dose limitation are met [14, 15]. In addition, contingency measures should be in place to deal with accidents and incidents so that any associated radiation hazards are controlled to the extent possible. This is described more fully in paras 5.39–5.59, which deal with the operation of the disposal facility.

3.4. Doses and risks associated with the transport of radioactive waste to the borehole disposal facility should be managed in the same way as those associated with the transport of other radioactive material. Of particular importance in this respect are external dose rates and contamination of waste packages (or any overpack used during transport). Transport safety is achieved by complying with the requirements of the Regulations for the Safe Transport of Radioactive Material [16].

Box 1: Radiation protection in the operational period

Requirement [7]

The radiation doses and risks to workers and members of the public exposed as a result of operations at the borehole disposal facility are required to be kept as low as reasonably achievable, economic and social factors being taken into account, and the exposures of individuals are required to be kept within applicable dose limits.

Criteria

Radiation dose limits and constraints for workers and for members of the public are set out in Schedule II of the Basic Safety Standards [7]. This publication in particular specifies that:

(a) "The occupational exposure of any worker shall be so controlled that the following limits be not exceeded:

— an effective dose of 20 mSv per year averaged over five consecutive years;
— an effective dose of 50 mSv in any single year" (Sche-II, para. II-5, Ref. [7]).

(b) "The estimated average doses to the relevant critical groups of members of the public that are attributable to practices shall not exceed the following limit:

— an effective dose of 1 mSv in a year" (Sche-II, para. II-8, Ref. [7]).

Members of the public could receive exposures from a number of practices and sources. To comply with the above limit, a "facility [such as a borehole disposal facility] (considered as a single source) is designed [and operated] so that the estimated average dose or average risk to members of the public who may be exposed in the future as a result of activities involving the disposal facility does not exceed a dose constraint of not more than 0.3 mSv in a year or a risk constraint of the order of 10^{-5} per year[a]" [8] (according to the models and assumptions recommended by the International Commission on Radiological Protection (ICRP)).

[a] Risk in this context is to be understood as the probability of death or serious hereditary disease.

Box 2: Radiation protection in the post-closure period [7, 8, 18]

Objective

"[Borehole] disposal facilities are to be sited, designed, constructed, operated and closed so that protection in the post-closure period is optimized, social and economic factors being taken into account, and an assurance is provided that doses or risks to members of the public in the long term will not exceed the applicable dose or risk that was used as a design constraint"[8].

Criteria

"The dose limit for members of the public from all practices is an effective dose of 1 mSv in a year [7], and this or its risk equivalent is considered a criterion not to be exceeded in the future. To comply with this limit, a [borehole] disposal facility (considered as a single source) is designed so that the estimated average dose or average risk to members of the public who may be exposed in the future as a result of activities involving the disposal facility does not exceed a dose constraint of not more than 0.3 mSv in a year or a risk constraint of the order of 10^{-5} per year[a]"[8].

In relation to the effects of human intrusion in the post-closure period, ICRP-81 [18] recommends that, if human intrusion is expected to lead to an annual dose of less than about 10 mSv per year to those living around the site, efforts to reduce the probability of human intrusion or to limit its consequences are not likely to be justifiable. If human intrusion is expected to lead to an annual dose of more than about 100 mSv per year to those living around the site, then it is almost always justifiable to make reasonable efforts at the stage of development of the facility to reduce the probability of human intrusion or to limit its consequences. Similar considerations apply where the thresholds for deterministic human health effects in relevant organs are exceeded. This recommendation of ICRP-81 [18] is not accepted by all regulatory bodies, however.

"It is recognized that radiation doses to individuals in the future can only be estimated and that the uncertainties associated with these estimates will increase for times further into the future. Care needs to be exercised in using the criteria beyond the time where the uncertainties become so large that the criteria may no longer serve as a reasonable basis for decision making"[8].

[a] Risk in this context is understood as the probability of death or serious hereditary disease.

RADIATION PROTECTION FOR THE POST-CLOSURE PERIOD

3.5. The primary goal of borehole disposal is to dispose of radioactive waste in a manner that protects human health and the environment in the long term, after the borehole disposal facility has been closed. In accordance with the BSS [7], this is achieved by means of design features that result in optimizing doses due to any migration of radionuclides from the facility while also complying with the dose constraints (see Box 2). It is recognized, however, that radiation doses and risks to individuals living in the distant future can only be estimated and the reliability of these estimates will decrease as the time period extending into the future increases (see paras III.2–III.11 of Appendix III). In this context, the optimization of protection is a judgemental process in which social and economic factors need to be taken into account, and it needs to be conducted in a structured but essentially qualitative way, supported by quantitative analysis. Optimization of protection in the post-closure period is explained further in para. 4.38.

3.6. A well-designed and well-located borehole disposal facility should provide reasonable assurance that radiological impacts in the post-closure period will be low both in absolute terms and in comparison with any other waste management options that are currently available at reasonable cost. A site should be identified that provides favourable conditions for containment and isolation of the waste from the biosphere and for preservation of the engineered barriers (e.g. with low groundwater flow and a benign geochemical environment). The borehole disposal facility should be designed to take account of the characteristics offered by the site, to optimize protection and to keep doses within the dose and/or risk constraints. The borehole disposal facility should then be constructed, operated and closed according to the assessed design so that the assumed safety characteristics of both the engineered and the natural barriers are realized.

3.7. In estimating the doses to individuals living in the future, it is assumed that humans will make use of local resources that may contain radionuclides that originate from the waste. The representation of future human behaviour in assessment models must necessarily be stylized, as it is not possible to predict future human behaviour with any certainty. The rationale and the possible approaches to the modelling of the biosphere and the estimation of doses arising as a result of the disposal of solid waste have been considered within the IAEA BIOMASS Project [17] (see Appendix III). In summary, Ref. [17] presents a methodology for the logical and defensible construction of 'assessment biospheres' (i.e. mathematical representations of biospheres used in the total system performance assessment for radioactive waste disposal). Reference [17] also presents a series of example reference biospheres: stylized assessment biospheres that, in addition to illustrating the methodology, are intended to be useful assessment tools in their own right.

3.8. Evaluating whether or not the design will provide an optimized level of protection may require a judgement in which other factors will be considered. These factors may include, for example, the quality of the design and of the assessment and the presence of significant qualitative or quantitative uncertainties in the calculation of long term exposures. In general, when irreducible uncertainties make the results of safety assessment calculations less reliable, then comparison with dose or risk constraints should be treated with caution. For a borehole disposal facility, such circumstances are likely to apply when considering:

(a) Design evolution (see definition in Appendix III) at very distant times in the future;
(b) Very low frequency natural events;
(c) Human intrusion events.

3.9. With respect to para. 3.8(a), it is recognized that there is an irreducible uncertainty associated with dose calculations for individuals living far into the future and this uncertainty will increase as the assessment time frame[1] increases. Sometimes, the assessment time frame is specified by the regulatory body; more often it defaults to a time longer than that required to reach peak dose. In the case of geological disposal, assessment time frames of a million years are not uncommon. However, where the wastes to be disposed of in a borehole disposal facility are fairly short lived (i.e. a few tens of years), the assessment time frame could also be relatively short (up to some hundreds of years), thereby diminishing the uncertainty associated with the calculations.

3.10. Very low frequency natural events could degrade the borehole disposal facility barriers, leading to the release of radionuclides to the environment and the exposure of humans to radiation. In circumstances where there is a significant uncertainty associated with the occurrence of an event or process and the consequent exposures, the level of safety is best demonstrated by separate consideration of the probability of occurrence and the potential

[1] The assessment time frame is the time period used in the calculations for the post-closure performance assessment.

magnitude of exposures. In these situations, the treatment of exposures far into the future is considered conceptually similar to potential exposure situations and can be treated in a similar manner [18, 19]. Again, as far as boreholes are concerned, the relatively short half-life of typical waste envisaged for disposal and the consequently shorter assessment time frame will tend to diminish the significance of very low frequency natural events.

3.11. In the event of inadvertent human intrusion into a borehole disposal facility, a few individuals who take part in activities such as drilling or excavating into the facility could receive high doses. The doses and risks to these individuals should be estimated but, according to the latest ICRP recommendations [18], they need not be a deciding factor in assessing the safety and acceptability of the facility. The doses and consequences of such intrusion should be estimated in order to evaluate and determine the appropriate measures (administrative and physical) necessary to prevent intrusion or to mitigate its consequences. Once it is determined that the disposal system includes appropriate deterrents to intrusion commensurate with the safety requirements and the potential consequences of such intrusion, the dose estimates for an intruder need not be used further. The borehole disposal system has a number of inherent features that reduce the likelihood and the consequences of intrusion. These include:

(a) The low probability of occurrence;
(b) The fact that the individuals would be few in number;
(c) The possibility for such individuals to receive appropriate decontamination and medical treatment;
(d) The fact that such hazards may be comparable with other occupational risks;
(e) The possibility that, while doses received due to inadvertent intrusion could be high, the associated risk may be outweighed by the higher level of long term protection afforded by borehole disposal, in comparison with other strategies.

It should be noted, however, that these particular ICRP recommendations are not accepted by all regulatory bodies. Where these recommendations are not accepted, the consequences for the intruders of human intrusion will also need to be addressed.

3.12. A more significant consequence of intrusion is the possibility that it could disrupt the engineered barriers and cause long term harmful consequences for people living in the vicinity of the borehole. In this case, protection is best achieved by means of efforts to reduce the probability of such events. One option is to assess the consequences of human intrusion, for which one or two stylized human intrusion scenarios should be evaluated using the criteria described in Box 1 [18]. Other approaches to assessing the consequences of human intrusion may also be acceptable.

3.13. The small 'footprint' of a borehole disposal facility will help to reduce the probability of human intrusion and this can be reduced still further by increasing the depth and length of the disposal zone. Siting of the facility away from known mineral and water resources will also decrease the likelihood of human intrusion. Over shorter timescales, actions such as preserving records, placing restrictions on land use, placing warning signs and maintaining passive institutional control should also help to reduce the incidence of such events.

ENVIRONMENTAL AND NON-RADIOLOGICAL CONCERNS

3.14. In this section, the protection of the environment from the radioactive material in the borehole disposal facility, especially over the long term, is considered. An important additional consideration is the potential impact of non-radioactive substances in the borehole disposal facility. Other, more conventional, environmental impacts, for example, traffic, noise, visual amenity, disturbance of natural habitats and restrictions on land use, together with social and economic factors, may well be subject to regulatory approval, but these fall outside the scope of this Safety Guide.

3.15. In the past, it has been assumed that, subject to appropriate definition of exposed groups, the protection of humans against the radiological hazards associated with a borehole disposal facility would also satisfy the need to protect the environment [19]. The need to consider the protection of the environment against ionizing radiation and possible protection standards is currently under discussion internationally (see, for example, Ref. [20]) and developments are to be expected in this area. It is likely, nonetheless, that in most circumstances the protection of humans will also protect the environment. However, the expectation is that, in future, methodologies for the assessment of doses to other species will allow this to be demonstrated explicitly [21].

3.16. Consequently, while recognizing that estimates of future human doses/ risks due to future releases from a borehole disposal facility may serve as indicators of environmental protection, additional indicators that do not rely on assumptions about human habits may also prove valuable. These indicators could include, for example, comparisons of repository derived radionuclide concentrations in environmental media with natural radionuclide concentrations and comparisons of radionuclide fluxes from a repository with fluxes from naturally radioactive mineralization [22].

3.17. The impact of non-radioactive materials present in a borehole disposal facility should also be assessed. Factors that should be considered may include the content of chemically or biologically toxic materials in the waste or in the engineered barrier materials, the protection of groundwater resources and the ecological sensitivity of the environment into which contaminants may be released. For example, if disused sealed sources were to be disposed of together with their lead shielding, safety assessments would need to examine the potential migration of the lead.

4. SAFETY IN THE PLANNING OF NEW BOREHOLE DISPOSAL FACILITIES

GENERAL

4.1. This section provides guidance on how, for a new borehole disposal facility, the predisposal activities may be organized to deliver the required operational and post-closure safety (i.e. how the protection requirements and associated criteria specified and discussed in Section 3 may be satisfied).

4.2. The guidance is set out under four main headings: (i) legal and organizational framework, (ii) safety approach, (iii) safety design principles and (iv) security.

LEGAL AND ORGANIZATIONAL FRAMEWORK

4.3. The discussion of the legal and organizational framework is subdivided into the responsibilities of government, regulatory bodies (‘the regulatory body’), facility developers and operators or would-be operators (‘the operator’) and waste generators. The overall aim is that the safety and security of potential radioactive waste should be provided for at all stages of waste management from creation through to disposal. Particular attention should be given to the issues of the appropriate legal and regulatory framework and the allocation of adequate financial resources. Funds will be required for disposal and for regulatory review and assessment. Consideration should be given as to when and how financial and legal responsibilities for the waste might pass from one body to another.

Government responsibilities

4.4. General requirements for establishing a national system for radioactive waste management are set out in Ref. [23]. In addition to the development of the necessary technical and operational capability, ensuring the safe management of radioactive waste requires relevant laws and regulations, a regulatory body that is independent of the operator, and a regulatory process that defines the steps to be taken in the licensing and development of the facility. Legislation should require a demonstration of safety and should require that the demonstration be independently reviewed by the regulatory body. Such provision is a principle of the Safety Fundamentals [13], is also required under the terms of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [1] and is a requirement for government responsibility for geological disposal established in Ref. [8].

4.5. The effort required under the legal and regulatory arrangements for controlling radioactive waste disposal in boreholes should reflect the potential hazard represented by the waste. Where small scale disposal of disused sealed radioactive sources is envisaged, the extent and complexity of the legal and regulatory arrangements should be commensurate. Matters that should be considered in the formulation of a national policy for radioactive waste management include the following:

(a) The early establishment of a comprehensive national inventory of radioactive waste will help to ensure that the resources and the facilities envisaged to deal with the waste will be adequate so that, for instance, late design changes are not introduced to cope with initially unforeseen waste. In general, it is the amount (i.e. volume, activity) and nature (e.g. half-life and physicochemical properties) of the inventory that should largely determine the resources needed for its disposal.
(b) The definition of the overall process for the development of borehole disposal facilities should clearly specify the legal (e.g. licensing) requirements at each step (see para. 5.1).

(c) The means of making the necessary scientific and technical expertise available to both the operator and the regulatory body should be considered. For instance, the government may require the national institutes for geology and hydrology to maintain or develop competence in this field so that they can give support to the regulatory body.
(d) The interdependences between the various steps in the waste management process should be considered so that, overall, the safety and the effectiveness of radioactive waste management are balanced.

4.6. The national policy and regulations should include the establishment of an operator with appropriate duties and responsibilities. This may, for instance, be a government department that then designates or subcontracts an expert body (or bodies) to design, build and operate the required facilities.

Responsibilities of the regulatory body

4.7. The regulatory body should advise the government on the necessity for, and the effectiveness of, the national policy for radioactive waste management and should provide assistance in its updating and improvement.

4.8. As with any other practice for radioactive waste disposal, the regulatory body should establish regulatory arrangements for borehole disposal facilities (see, for example, the requirements for regulatory body responsibility for geological disposal established in Ref. [8]). The regulatory arrangements should be established after consultation with all interested parties and they should be settled well in advance of any licence application. The arrangements should cover all stages of the development process for the facility, specifying the principles, requirements and criteria that will be used to regulate the practice and stating what should happen in the event of non-compliance. The arrangements should also cover more general issues such as:

(a) Clearance levels for waste with very low levels of radioactivity and the arrangements for regulating the release of such material [24];
(b) Regulatory approval of storage of radioactive waste prior to disposal;
(c) Licensing of borehole disposal at an existing radioactive waste disposal facility.

4.9. The regulatory body should also provide guidance on the implementation of the regulations, on the procedures that the operator is expected to follow in terms of licence applications and safety case submissions, on the timescales likely to be required for consideration of the licence application, and on the likely duration of any period of institutional control. While the regulatory arrangements should be comprehensive, they should also be commensurate with the scale and potential hazard of the facilities under regulatory control.

4.10. A licence for construction and operation of the facility will be issued only when, following regulatory review and assessment of the licence application, there is reasonable assurance that the safety requirements will be met and it is clear that funds are, or will be, available to finance the programme through all its stages (i.e. construction, operation, closure and any planned post-closure institutional control period). As explained in para. 5.1, a step by step approach to licensing and implementation should clarify the decision making process and highlight the key issues that will influence the various decisions. The licence application at each step should describe, as far as is known, the entire disposal programme so that early steps in the disposal programme can be seen to be compatible with later steps.

4.11. It is good practice for the licence to have sufficient flexibility to accommodate, through a change control process, unforeseen changes (e.g. in design) made as a result of improved knowledge. The conditions under which the operator can make changes without needing to apply to the regulatory body for permission should be specified in the licence. The burden imposed by the change control process should be commensurate with the size of the potential hazard.

4.12. Independent regulatory review and evaluation of the safety case (see paras 5.12 and 5.13) may vary considerably depending on the existing national regulatory practice, the potential hazard of the waste and the stage reached in the development process of the facility. The regulatory body should ensure that it has the independent capability to carry out the review and evaluation of the safety case that is needed to determine whether the facility will be safe and what conditions of authorization should be specified in the licence. This may be undertaken in various ways, such as by consultation with independent experts, by collaboration with other States that are using similar processes and by the use of generic safety assessment.

4.13. When it is envisaged that a disposal facility will remain in operation for some years, with new boreholes being added from time to time, safety should be reassessed periodically. Alternatively, the licence could approve the site but require that each new tranche of boreholes be licensed separately. This would allow the regulatory body formally to reassess safety as operation of the site yields new data and as safety standards are developed. Either way, requirements for the reassessment of safety should be made clear early in the development process for the facility.

4.14. The regulatory body should ensure that the operator exercises adequate control at all stages in the development of the borehole disposal facility. A regulatory inspection plan should be developed for activities important to safety, such as construction, operation and closure. The regulatory inspections will help to ensure compliance with the licence and the operational procedures (e.g. acceptability of waste packages and their satisfactory emplacement). Appendix I provides an example of a regulatory inspection plan for a borehole disposal facility. When non-compliances are discovered, the actions required by the regulatory body should reflect the safety significance of the non-compliance. Very serious cases should result in activities at the site being restricted or curtailed. Minor breaches may simply require remedial action.

4.15. In some States, it is normal for borehole or surface disposal facilities that have been closed to be periodically reassessed for safety in the light of monitoring results and such good practice should be adopted.

Operator responsibilities

4.16. The requirements for operator responsibility for geological disposal established in Ref. [8] place an obligation on the operator to develop a disposal facility that is both practicable and safe and to demonstrate its safety in compliance with regulatory requirements. In some cases, this may include collection of the waste at the waste generators' premises and its transport to the disposal site. In meeting this obligation, the operator should take into consideration the characteristics and quantities of disused sealed sources that are radioactive and other radioactive waste to be disposed of, the transport infrastructure, the sites available, the drilling and engineering techniques available, research needs and the national legal framework and regulatory requirements. Where the operator employs contractors to perform the work, the operator is responsible for ensuring that they also comply with the regulatory requirements.

4.17. The operator is charged in particular with the responsibility for preparing and submitting to the regulatory body a safety case (see paras 5.2–5.13) on which decisions about the development of the disposal facility can be based. Borehole construction should not proceed until a licence has been granted.

4.18. The operator should be responsible for conducting or commissioning the research and development needed to support the feasibility and safety of the facility design. This should include site investigations. The operator also has the responsibility for carrying out or commissioning all the investigations of sites and materials necessary to assess their suitability and to provide data for safety assessments. In the case of borehole disposal facilities, it is envisaged that the designs will rely almost entirely on tried and tested materials and working practices. This will largely confine research to desk studies and will shift the emphasis of the work towards demonstrations of the operability of the design and the suitability of the site.

4.19. The operator should establish and set limits, controls and conditions (e.g. technical specifications) derived from the safety assessments to ensure that the disposal facility is developed and operated in accordance with both the safety case and the licence conditions. This will require the recruitment and training of suitably qualified staff, the exercise of due control over the receipt, transport and emplacement of waste (e.g. waste acceptance criteria, see para. 5.60), and the implementation of appropriate security measures. Any changes to the design or operation of the facility that may have a potential impact on safety should be subject to a change control process (see para. 4.11).

4.20. The operator should retain all the information relevant to the safety case, the supporting safety assessments for the disposal facility and the inspection records that show compliance with regulatory requirements and the operator's own specification, at least up until the information is superseded or responsibility for the disposal facility is passed to some other appointed agency (e.g. at closure). When this responsibility is transferred, the operator should hand over all the information that is relevant to the safety of the facility. The operator should also cooperate with the regulatory body and supply all the information that the regulatory body may require to fulfil its responsibilities. The operator should report to the regulatory body on a regular basis and should report on non-compliances as they occur.

4.21. The operator should take full responsibility for the waste upon receipt. The operator should also have the responsibility for verifying that the waste is fully and correctly described in the accompanying documentation. The description may include the dose rate at the surface of the package and at 1 m distance, as well as details of removable surface contamination, volume, mass and physical status, and chemical and radionuclide composition of the waste.

Responsibilities of the generator of the radioactive waste

4.22. The generator of the radioactive waste should work with the regulatory body and the operator to ensure that the waste can be safely managed through all steps of the waste management process. In recognition of the interdependences between the various steps in waste management from waste generation to disposal, in making decisions relating to one step, the impacts and/or the needs of subsequent steps should be considered. This will require coordination of activities and the timely exchange of information. The generator of the waste should not treat, condition (including encapsulation) or store the waste in an inappropriate way or do anything that will make the waste more difficult to manage at a later stage in the waste management process.

4.23. The generator of the waste should characterize the waste and treat and condition it to ensure compliance with the waste acceptance criteria that are specified by the operator and approved by the regulatory body (see paras 5.60–5.65), unless this is the responsibility of the operator. Adequate characterization, treatment and conditioning may be ensured by independent inspection and audit of the various processes and representative sampling from the waste packages that have been produced.

4.24. Generators of waste should also maintain records. For sealed sources, for instance, purchase details should be preserved, together with a history of their usage, and instances of damage especially should be recorded. The generator of the waste should also have responsibility for the safe transport of the waste to the operator's site, unless the operator takes over this responsibility before the waste leaves the premises of the generator of the waste.

SAFETY APPROACH

4.25. Even a relatively straightforward borehole disposal facility may take several years to develop. Key decisions, for example, on siting, detailed design, construction, operational management and closure, are expected to be made as the project develops. Decisions will be made on the basis of the information available at the time and the confidence that can be placed in that information. Decisions on facility development will be influenced by external factors, such as national policies and preferences and the availability of a suitable host geology.

4.26. In accordance with the requirements concerning the importance of safety in the development process established in Ref. [8], at each major decision point, the safety implications of available options are considered and taken into account. Ensuring safety is the overriding factor at each decision point. If more than one option is capable of providing the required level of safety, then other factors may also be considered. These other factors may include public acceptability, cost, security, site ownership, existing infrastructure and transport routes.

Passive safety

4.27. A borehole disposal facility should be sited, designed and constructed so that, when closed, the post-closure safety of the facility will not depend on actions that would need to be taken after the closure. This allows the facility to comply with the requirements concerning passive safety established in Ref. [8].

4.28. The requirement to provide for safety by means of passive design features means that for the post-closure period there should be no need for active management of a borehole disposal facility once this phase is reached. For boreholes of an intermediate depth (i.e. boreholes where the waste is placed more than 30 m below the surface), the natural and engineered characteristics of the closed disposal system should be sufficient, on their own, to ensure the safety of the waste and the protection of people and the environment. In the case of near surface boreholes (where waste is less than 30 m below the surface), institutional control to reduce the risk of human intrusion may also be an element of the safety case. Near surface boreholes are not likely to be suitable for waste that would pose unacceptable risks associated with human intrusion or security. Institutional controls and monitoring are discussed further in paras 5.68–5.80.

4.29. In practice, even for intermediate depth boreholes, passive institutional controls, including controls on land ownership and restrictions on land use, could be maintained for some time after closure of the facility to reduce further the possibility of inadvertent intrusion and to provide additional public assurance. This would facilitate, among other things, monitoring for the purpose of providing assurance and confidence in the safety of the facility.

4.30. Regardless of the degree and duration of post-closure institutional control, safety assessments should be conducted with the aim of providing reasonable assurance of an adequate level of passive safety for boreholes of both types. Factors contributing to passive safety include the use of chemically stable waste forms, high integrity containers, borehole backfill between the containers and the borehole casing, disposal at a depth greater than 30 m, non-chemically reactive groundwater, stable geology and disposal in a location that benefits from a low probability of human intrusion.

4.31. Passive safety is not a requirement for the operational period, although, clearly, if the operational activities are organized to reduce the number of active measures needed to ensure safety, this will be beneficial. An example is the incorporation of shielding in packages to allow them to be contact handled. Passive safety is also assisted by keeping the operational period short. For instance, to avoid keeping a borehole open for an extended period, it may be preferable to drill, construct, emplace, backfill and close a borehole only when there is sufficient waste for disposal to allow this full sequence of activities to be enacted. This may require the capability to store the waste safely at the facility for a period of time.

Adequate understanding of, and confidence in, safety

4.32. A borehole disposal facility should be designed and sited so that there is sufficient understanding of the features, events and processes that influence post-closure safety to gain the reasonable assurance of safety that is required to be established. This understanding should cover the time period during which the waste constitutes a significant potential hazard or, at least, over the time frame of the post-closure safety assessment (which may be fixed by regulation or agreed with the regulatory body).

4.33. The understanding of the behaviour of the system in the post-closure period will evolve as more data are accumulated and as scientific knowledge is developed. Early in the development of the concept, the data and understanding should be sufficient to give the confidence necessary to commit the resources to further investigation. Before the start of construction, during emplacement and at closure, the understanding embodied in the safety case should be sufficient to give reasonable assurance that the relevant regulatory requirements will be satisfied. Demonstrating reasonable assurance entails the presentation of an assessment of the safety of the total disposal system together with the uncertainties in the assessment. This will be facilitated by identifying the system's features and processes that provide safety and also the external features, events and processes that might be detrimental to safety, and showing that these and their interactions are sufficiently well characterized and understood.

4.34. A database of features, events and processes relevant to near surface disposal is under development by the IAEA [25]. This constitutes a useful starting point for the compilation of a list of features, events and processes for borehole disposal. Which features, events and processes are relevant and which are not will depend on the specific circumstances. Some features, events and processes will clearly need to be incorporated into the post-closure safety assessment. Radionuclide solubility, for instance, will almost always be included. Other features, events and processes will clearly not be relevant. For the majority of features, events and processes, though, the question of whether to include them or not will be a matter of judgement. Guidance can be obtained by referring to previous examples of safety assessments (see, for example, the generic borehole post-closure assessment described in Ref. [26]). Most important of all is the acknowledgement of the exclusion or omission of any features, events and processes, together with the underlying reasoning.

4.35. Confidence in post-closure safety is considerably improved by the adoption of methodologies that are both comprehensive and systematic. Useful guidance in this connection has been provided by the OECD Nuclear Energy Agency [27] and through the IAEA's ISAM project [28]. Paragraph 5.2 of this Safety Guide further discusses this aspect.

Optimization of protection

4.36. Ensuring that doses will be below the regulatory approved dose constraints is a necessary but not by itself sufficient condition for regulatory approval. This is because, for the optimization of protection, it is required that if safety can be enhanced without undue detriment, then it should be, economic and social factors being taken into consideration. Optimization of protection will often be judgemental because the decision on when a detriment changes from being acceptable to being undue will ultimately depend on the individual circumstances and the value judgements of those doing the judging. It follows that the optimization of protection is an issue that should be discussed in the light of the individual circumstances and, wherever possible, agreed in advance with the regulatory body. Safety assessments provide some of the most important inputs to the process of optimization.

4.37. The optimization of protection during the operational phase of a facility is a key element of the design of the disposal facility itself, the predisposal facilities and the above ground operations. Relevant considerations include the separation of drilling and waste emplacement operations, the use of remote handling and radiation shielding during predisposal and disposal operations, the control of working environments, the reduction in the potential for accidents and their consequences and the minimization of maintenance requirements in radiation and contamination areas. Many of these issues are common to the operation of nuclear facilities generally and guidance is available [29].

4.38. The optimization of protection for the post-closure period entails taking judgemental decisions [18]. However, a judgement on whether protection for a proposed disposal facility has been adequately optimized or not should still be capable of resolution using objective criteria. Protection should be deemed to be optimized if all the following conditions are met [18], namely, that:

(a) Due attention has been paid during the development process to the post-closure safety implications of the various options, which should include all the design and siting related issues discussed in paras 5.14 and 5.20;
(b) The assessed doses and risks fall below the relevant constraints;
(c) The probability of any events that might give rise to doses above the dose constraint has been reasonably reduced by means of siting or design;
(d) The design, construction, operation and closure programmes have been subjected to a management system which will ensure the necessary level of quality in safety related aspects of the project.

4.39. In some cases, there may be competing demands between operational and post-closure safety. A higher standard of packaging (e.g. a fully welded container or waste treatment to avoid gas generation) may benefit post-closure safety at the expense of somewhat higher occupational doses during predisposal activities (though doses should still fall below the regulatory dose constraint). It should be the responsibility of the operator to design the facility so that an appropriate balance is reached between any competing demands.

SAFETY DESIGN PRINCIPLES

4.40. In general, post-closure safety is achieved by designing and implementing a disposal system in which the components work together to provide and ensure the required level of protection. This approach offers flexibility to the designer of a borehole disposal system to adapt the facility layout and engineered barriers to take advantage of the natural characteristics and barrier potential of the host environment. Operational safety should also be ensured and this may require consideration of a number of complex issues, including the possible impact of predisposal and disposal operations on the post-closure performance.

Containment

4.41. The requirements concerning containment established in Ref. [8] call for the engineered barriers[2], which include the waste form and packaging, to be designed and the natural barriers to be selected to provide containment of the radionuclides in the waste, especially during the initial period when the level of activity is most intense and radioactive decay can significantly reduce the hazard posed by the waste. This will allow the majority of shorter lived radionuclides to decay in situ. At the same time, release of gaseous radionuclides and a small fraction of some other highly mobile species may be inevitable from waste package of some types, but generally these radionuclides present relatively minor radiological hazards. In any event, the safety assessment should demonstrate that doses and risks arising from such releases fall within the regulatory constraints.

4.42. Waste of higher radiotoxicity, which may include some disused radioactive sources, can be surrounded by an encapsulation matrix and placed in durable containers. The purpose of the encapsulation matrix is to contain the radionuclides in the waste through a combination of physical and chemical functions that are effective for hundreds or even thousands of years. Other engineered barriers, such as a borehole backfill, may allow this containment period to be extended even further, but complete containment of all radionuclides for all time cannot be expected. Containment of radionuclides is also provided by the natural barriers by means of geochemical and physicochemical retention processes that lead to retardation of the transport of radionuclides in the geosphere. Evidence from natural analogues indicates that these processes can be effective over very long timescales.

4.43. A 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 may be relatively straightforward and cost effective to select an appropriate geological horizon (and therefore a suitable hydrogeological condition) for the disposal, with due consideration given to the containment of radionuclides and their isolation from humans. It is envisaged that the appropriate depth would lie in an

[2] A barrier in this context is a physical obstruction that prevents or inhibits the movement of radionuclides, or provides shielding against radiation. There are two types of barrier: engineered barriers and natural barriers. In this context, a barrier is a physical entity that provides, or contributes to, safety.

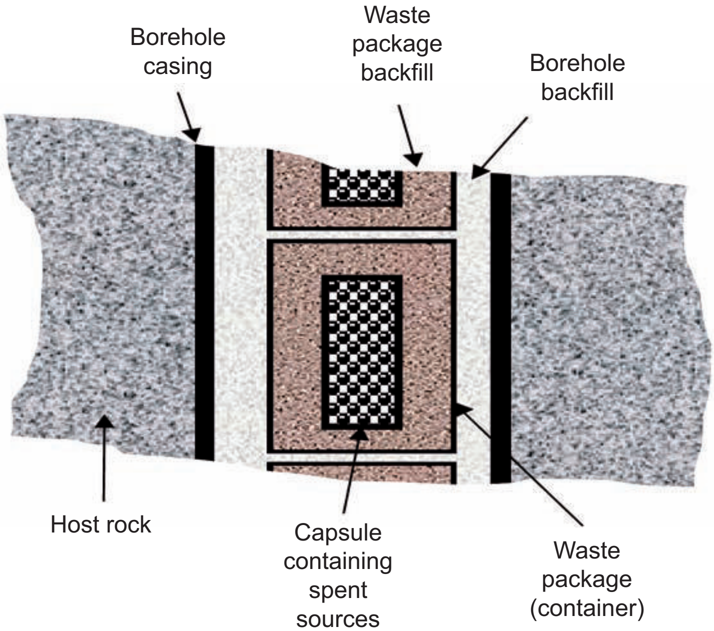

FIG. 2. Scheme of some possible components of a borehole disposal system.

intermediate depth range (e.g. 30 m to a few hundred metres), between near surface and deep geological disposal. Figure 2 shows some typical components of a borehole disposal system.

Isolation

4.44. While containment refers primarily to the radionuclides in the waste, isolation is more concerned with the waste itself and the need to keep this potentially dangerous material away from humans, human influence, resources used by humans and the biosphere for as long as it remains a significant hazard. The isolation period of ‘several thousand years’ mentioned in the requirements concerning containment established in Ref. [8] would not apply if the radionuclides in the waste were short lived. In choosing sites, consideration should be given to erosion, tectonic uplift and landslip that might cause the waste to be brought close to the surface over the assessment period. One of the aims of isolation is to prevent human intrusion, which could affect the subsequent isolation of the waste and containment of the radionuclides within it. It is clear that isolation is also important in promoting security. While human intrusion is inherently unpredictable, some actions can be taken at the design stage to lessen both its probability and its consequences. If possible, for instance, borehole disposal facilities should be located away from known underground mineral and water resources. In general, disposal at greater depth should improve security and should help to reduce both the probability and the consequences of human intrusion.

4.45. In the absence of institutional control, a depth of 30 m should be considered the minimum necessary to achieve waste isolation. This should therefore be the minimum depth required for waste that might constitute a security risk (see paras 4.52–4.54). However, for waste that would otherwise be eligible for near surface disposal and for short lived radionuclides, where the waste may no longer constitute a hazard after, perhaps, one hundred years, disposal at a shallower depth together with institutional control could be an option. Engineered anti-intrusion barriers that are mechanically strong and heavy may also be useful in enhancing isolation. For a small scale borehole disposal facility, the resources needed for institutional control could be reduced by locating the boreholes at a site with an existing security infrastructure, for example, at an existing nuclear facility.

4.46. For waste placed deeper than 30 m, isolation is primarily provided by the geosphere and the main factors to be considered in determining a depth that will provide an appropriate level of isolation are the rate of surface erosion, the timescale of the assessment and the depth of any permafrost. Of course, isolation is not the only issue to be considered when determining borehole depth: the influence of the host geological environment on containment should also be considered.

Multiple safety functions

4.47. A safety function is a specific purpose that must be accomplished for safety; the safety function could be provided by a physical or chemical quality or process that contributes to safety. Examples of safety functions include low groundwater flux, impermeability to fluids, resistance to corrosion, insolubility of radionuclides, adsorption of radionuclides onto engineered materials and surrounding rocks and disposal in geological formations having a low groundwater flow. In the case of a near surface disposal facility (i.e. where the waste is within 30 m of the surface), it is reasonable for administrative measures (i.e. an institutional control period during which the waste decays to insignificant levels) to provide a safety function [9].

4.48. To provide confidence in long term safety, a waste disposal system should employ a number of complementary engineered and natural barriers. Often, these barriers will be effective over different timescales and will provide a number of safety functions. Depending on the hazards associated with the waste, the barriers may vary in number and complexity. They may include, for instance:

(a) A waste container made of a corrosion resistant material that gives a container lifetime of about a thousand years;
(b) A cement based backfill placed between the container and the borehole casing to create high pH conditions that limit solubility and promote sorption and so provide chemical containment for thousands of years;
(c) A location where the rate of groundwater movement and the degree of radionuclide sorption onto the surrounding rocks together ensure that the radionuclides would take many thousands of years to migrate to the biosphere.

4.49. Although the safety of a borehole disposal facility will ultimately be judged by global measures of the total system performance, these barriers should not be unduly dependent on each other. So, for instance, in the example just outlined, the container lifetime may be extended by the high pH conditions provided by water leaching from the cement backfill, and the longevity of the backfill will be assisted by low groundwater flow. However, a groundwater flow that is higher than expected should not result in rapid corrosion of the container and the release of its contents. Similarly, failure of the cement to provide the expected high pH conditions should not lead to failure of the container or a more rapid migration of radionuclides through the surrounding rocks. These unwanted possibilities could be prevented by using a container material that shows adequate corrosion resistance over a range of pH conditions and sufficient cement backfill to provide long lived high pH conditions even if the groundwater flow were at the top end of the range of possibilities. In this way, a worse than expected performance from one of the barriers would not lead to the failure of the entire system.

4.50. Multiple barriers and multiple safety functions should be used to enhance both safety and confidence in safety by ensuring that the overall performance of the disposal system is not unduly dependent on a single barrier or function. This should provide reasonable assurance that, if a barrier does not perform as expected, then a sufficient margin of safety remains (see the requirements for multiple safety functions established in Ref. [8]).

4.51. The various components of the engineered and natural systems also need to be complementary. Examples of non-complementary components are:

(a) The use of ordinary Portland cement when the surrounding groundwater or geology has high levels of sulphate (common in some types of clay);
(b) The use of swelling clays in highly saline environments or in groundwater with high levels of potassium.

SECURITY

4.52. It is a requirement of the BSS that "sources shall be kept secure so as to prevent theft or damage…" (para. 2.34, Ref. [7]). The operator of a borehole disposal facility will be responsible for the security of the waste from the time it is received from the waste generator. If the handover occurs at the waste generator's premises, the operator will also be responsible for the safety and security of the waste during its transport through the public domain to the waste conditioning and/or waste disposal site [30]. Precautions should be taken at the disposal site to prevent persons from carrying out unauthorized actions that might jeopardize safety or allow unauthorized removal of the waste [31]. The extent of security arrangements should reflect the potential for damage to the facility and the assessed risk of unauthorized removal of the waste. The arrangements should, at least, include measures to prevent unauthorized access to the site during site operations. Clearly, waste such as high activity disused sealed radioactive sources will require stricter security than low level waste. Arrangements and appropriate liaison with competent authorities should be established to obtain timely assistance if this is required.

4.53. In the case of disposal in near surface facilities, the proximity of the waste to the surface may make it appropriate for security measures to be continued into the post-closure period to prevent human intrusion and/or unauthorized removal of the waste. The security measures would remain in place until the sources no longer constituted a potential hazard. In general, waste that constitutes a significant security risk (e.g. sealed radioactive sources for which the radioactive material is in a dispersible form) will not be suitable for near surface disposal.

4.54. Even where all the waste in a borehole disposal facility is placed at a depth of more than 30 m, a site security presence will be required throughout the operational period. In cases where disposals occur in a series of campaigns, it may be preferable to seal all the boreholes that contain waste at the end of each campaign. Subsequent sealing of the boreholes (para. 5.53) and closure of the site (para. 5.66) should aim to allow the lifting of security measures at the site.

5. SAFETY AND DISPOSAL IN NEW BOREHOLE DISPOSAL FACILITIES

FRAMEWORK FOR DISPOSAL

5.1. Consistent with requirements for step by step development and evaluation in Ref. [8], the appropriate framework for the development of a geological disposal facility is a step by step approach that is supported, through all stages of the project, by iterative evaluations of the design and management options, system performance and overall safety. This is necessary owing to the extensive investigation and assessment required to provide sufficient confidence to move through the various stages in the lifetime of the facility and associated licensing activities. The development framework will normally be specified in the governing legislation. A step by step process for a small disposal programme will need less investigation and assessment, and an example of an appropriate programme is provided in Appendix II.

SAFETY CASE AND SAFETY ASSESSMENTS

General

The safety case

5.2. The safety case comprises the collection of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in safety, of a radioactive waste disposal facility. The safety case is an essential input into all the important decisions and authorizations that concern the facility. It provides the arguments as to why the facility is considered to be safe and includes the safety assessment (see below) and other analyses explaining the relevance of the various arguments and their strengths and weaknesses. After disposal, some of the information in the safety case, specifically that concerned with the post-closure safety of the facility (see paras 5.68–5.73 on post-closure institutional controls), should be preserved for the benefit of future generations. This information should be defined, compiled and placed in suitable storage (e.g. a national archive).

5.3. The safety case may also need to cover other issues arising from legislation on environmental impact assessment and, less formally perhaps (though no less importantly), the need for public acceptance.

5.4. The safety case should be a 'living document' that is developed in parallel with the development programme for the waste disposal facility. Regardless of the stage that the programme has reached, a safety case submitted for regulatory scrutiny should cover the complete programme (even though this may not have been fully developed) so that the regulatory body can put the licence application into its correct context. This includes areas where there are significant uncertainties and the work planned to reduce them. The overall aim is to demonstrate, with a level of confidence appropriate to the stage that the programme has reached, that the complete programme is feasible and can be completed to plan.

Safety assessment

5.5. Safety assessment is an essential part of the development of any radioactive waste disposal facility. It can be used to examine the safety of a complete proposal or any aspect of it, such as transport, operation or the post-closure period, or any part of these. The step by step approach encourages the various iterations of the safety assessment to be progressively developed as the project moves through its different stages. Early in the process, the safety assessment will tend to be generic (i.e. non-site specific). Later, the safety assessment will become progressively more site specific. Safety assessment provides inputs to ongoing decision making in relation to, for example, the selection of conceptual designs, guidance of research, site selection, site characterization, development of assessment capability, allocation of resources (including funding) and the development of waste acceptance criteria. The safety assessment will also identify key safety relevant processes and contribute to developing an understanding of the operational safety of the disposal facility and its post-closure performance. This understanding provides the basis for the safety arguments presented in a safety case.

5.6. The timing and level of detail of the safety assessment are a matter for the operator in consultation with the regulatory body. In the case of a small scale borehole disposal facility, where the small inventory results in the calculated dose falling well below the regulatory constraint (i.e. there is a large margin of safety), it is likely that the safety assessment and the associated investigations would be relatively simple. Appendix III provides further information on the safety case and safety assessment for borehole disposal facilities.

Generic safety assessment

5.7. Generic (i.e. non-site specific) safety assessment is a tool that can be used in many aspects of a waste disposal programme. For example, at the concept development stage and in support of site screening, generic safety assessment can be used:

(a) To help identify radionuclide inventories suitable for disposal;
(b) To help determine suitable levels of engineering;
(c) To help determine suitable site characteristics;
(d) To help determine the need for, and duration of, an institutional control period.

5.8. Even when a site has been chosen for investigation, generic safety assessment may help in:

(a) Identifying the key parameters that need to be characterized for a site specific assessment and the extent of site characterization required;
(b) Providing a basis, consistent with good practice, for any site specific assessment that might be undertaken and helping to build confidence in that site specific assessment.

In such cases, rather than developing a site specific safety assessment, it could be sufficient to undertake site specific investigations to confirm that the site conditions, design and inventories fall within the generic safety assessment's envelope of assumptions and data.

5.9. Generic safety assessment in general may also be used to examine operational and transport safety (see, for example, Refs [32] and [33]), and a separate report has been developed on such a generic safety assessment for the small diameter borehole concept design. The annex to this Safety Guide is based on a report on generic safety assessment.

Site specific safety assessment

5.10. Once a site has (or sites have) been selected for detailed investigation, post-closure safety assessment (in particular) will be an important determinant for the site characterization programme(s). By replacing some of the generic information contained in the safety case with site specific information, the site specific safety assessment covering all aspects of safety can then be developed with the aim of determining whether disposal facilities constructed at a site would be capable of meeting the regulatory requirements. These site specific safety assessments will be an important component of the safety case for the site. Where a generic safety assessment has been performed, it may be possible to simplify the site specific assessment by limiting it to a confirmation that, in all important respects, the safety of the proposed facility is adequately described by the generic safety assessment.

5.11. Where it is proposed to create a borehole disposal facility at an existing near surface disposal site, the impact of the borehole disposal facility on the safety of the near surface facility and vice versa should be considered. This may be best done by modifying the existing safety assessment to include the proposed borehole disposal facility. A relatively straightforward modification of the safety case may be possible in the case where the proposed borehole contains similar waste which is emplaced at a depth similar to that of the near surface facility. Where the proposed borehole extends to greater depths, the effects on the safety case will be more far reaching, since the consequences of placing radionuclides in a different geological and/or hydrogeological horizon should be considered.

Independent review and assessment

5.12. The operator of a borehole disposal facility should submit the safety case and its associated safety assessment to the regulatory body for independent review and assessment. The principal aim of the review is to judge the quality of the safety case in the context of the regulatory requirements and the stage that the project has reached. Essentially, this requires an examination of the arguments, data and level of understanding (e.g. uncertainties) presented by the safety case.

5.13. Independent review and assessment should judge, among other things, whether:

(a) The safety requirements will be complied with.
(b) The safety case contains sufficient detail.
(c) The data and information presented are sufficiently accurate.
(d) The safety case demonstrates that the design has been optimized and, with reasonable assurance, that the safety objectives and criteria will be met.
(e) The management system(s) is adequate (in this regard, separate Safety Guides are available for predisposal [34] and disposal activities [35]).
(f) The arrangements proposed for the preservation of records are adequate (more detailed guidance on this subject is presented in Ref. [35]).

DEVELOPMENT OF BOREHOLE DISPOSAL FACILITIES

Design of the disposal facility

General design considerations

5.14. Safety assessment is an important tool for demonstrating the optimization of the facility's design. The expected performance of the natural barriers in containing radionuclides will have implications for the required level of engineered containment and the way in which waste emplacement and borehole sealing operations and closure should be carried out. The choice of design for a borehole disposal facility will depend on many factors, including the quantity and nature of the waste to be disposed of, the availability of suitable disposal environments and the availability of appropriate engineering technologies and materials.

5.15. An important issue that should be decided relatively early in the programme is the selection of an appropriate design of waste package, i.e. the container and its contents. This is essential for both the predisposal and the disposal periods as it provides containment for the waste during storage, transport, disposal operations and the post-closure phases. Factors such as the amount of in-built shielding (and therefore the need to handle the waste package remotely) and the dimensions and weight of the waste package, lifting and handling arrangements, corrosion and radiation resistance and the method of emplacement in the borehole will all have an influence on operational feasibility and safety (see the discussion on the operation of the disposal facility in paras 5.39–5.59). The long term performance of the waste package may play an important part in the post-closure safety of the disposal system. The durability of the waste package will depend on the properties of the materials used in its construction and their interactions with the other engineered barriers and in the geochemical environment.

5.16. During the early development of the borehole disposal facility, a number of site, design and operational options will be available. Choices should be made with a view to striking an optimum balance of operability, containment and isolation within reasonable financial cost. The multiple safety function approach should be utilized so that the safety of the facility does not depend unduly on a single barrier or a single chemical or physical property. Safety assessment should be used to examine the various design options: first, to see whether compliance with the regulatory constraints is achievable, and second, to help deliver the constrained optimization described in paras 4.36–4.39.

5.17. It is likely that the operator will be given the task of disposing of a known volume and inventory of waste. The operator should then design a facility consisting of a single borehole or a series of boreholes to accommodate this waste. Clearly, there are many ways of doing this, ranging from a large number of small volume boreholes to a single, deep, large diameter shaft. The optimum design will depend on the individual circumstances, but some general points can be made:

(a) The risk arising from human intrusion will be reduced when the ‘footprint’ is small and the waste is placed below the residential intrusion zone.
(b) An increasing depth of disposal will usually increase the transit time for radionuclides to migrate to the surface; the main exception to this is when disposal at a lesser depth would allow disposal in the unsaturated zone or in very low permeability rocks.
(c) The variable cost component of excavation increases approximately exponentially with depth.

Choice of engineered barriers

5.18. The engineered barriers can provide a significant degree of containment for the radionuclides in the waste. The use of corrosion resistant materials should allow the engineered barriers to be sufficiently long lived to make a useful contribution to safety. Thus, the safety case should be able to take some credit for a period of containment within the package itself. The engineered barriers may include (see, for example, Fig. 2):

(a) The original casing (for disused sealed sources).
(b) Welded metal (e.g. plain carbon or stainless steel) capsules for some small volume waste (e.g. radium sources).
(c) A metal (e.g. plain carbon or stainless steel) waste container.
(d) An encapsulation matrix (e.g. cement grout, bentonite or lead) within which radioactive waste (e.g. radium sources) may be embedded, creating the waste form within the container[3].
(e) Borehole backfill (e.g. cement grout) surrounding the waste packages.
(f) Metal or plastic borehole casing to support borehole walls during drilling or emplacement operations; following waste emplacement, it may be beneficial to remove the casing above the disposal zone.
(g) Behind casing seal to fill any voids between the casing and the borehole.
(h) Borehole seal — a clay or cement plug several metres long placed in the borehole above the disposal zone (which can sometimes be complemented by a plug at the bottom of the disposal zone).

5.19. The effectiveness of, and confidence in the effectiveness of, the engineered barriers will be greatest when they employ a range of chemical and physical properties to contain the radionuclides. So, for instance, whereas the role of the waste container is primarily one of physical containment, a cement based encapsulation matrix can provide some chemical containment by reducing radionuclide solubility and providing surfaces that radionuclides can sorb onto. An important consideration in the choice of engineered barriers is their compatibility with the surrounding geochemical environment (e.g. para. 4.51) and their durability and integrity over the period of time for which the waste remains hazardous.

Site selection

5.20. In locating a suitable site for a borehole disposal facility, due consideration should be given to scientific, technical, socioeconomic and planning factors. Sites may be identified as possible sites in the selection process because they are on the locations of existing nuclear, waste

[3] The waste package is defined as the product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liner), as prepared in accordance with requirements for handling, transport, storage and/or disposal. This includes an outer container and, if included, an encapsulation matrix that fills the void space within the container. The waste form is the combination of waste and waste encapsulant.

management or governmental facilities and such sites are sometimes given a high weighting on the grounds of availability, practicality, transport needs and existing institutional control. A well-planned systematic approach will help with the site selection process and will provide opportunities for the involvement of stakeholders (interested parties). Meeting the required safety objectives is a primary consideration in site selection and the rest of this section focuses on this aspect.

5.21. General guidelines for siting radioactive waste disposal facilities are presented in two IAEA publications [36, 37]. However, the borehole concept requires some interpretation of these guidelines, not least because of the wide range of possibilities that it represents.

Site characteristics

5.22. Reference [9], in discussing the suitability of a site for near surface disposal, states that the following topics are required to be considered as a minimum: geology, hydrogeology, geochemistry, tectonics and seismicity, surface processes, meteorology, climate and the impact of human activities. Although primarily directed towards near surface facilities, investigation of these aspects can, with some change of emphasis for boreholes of intermediate depth, be used to evaluate:

(a) The possible contamination of groundwater resources.
(b) The impact of climate driven surface processes such as flooding, erosion, landslip or weathering on the capability of the disposal system to isolate the radioactive waste.
(c) The extent to which events such as faulting, seismic activity or volcanism could compromise the isolation capability of the repository.
(d) The extent to which foreseeable human activities could compromise the isolation capability of the repository; this requires the consideration of land ownership and the resource and development potential of the site and its immediate surroundings.
(e) The extent to which the geochemistry of the surrounding area could impair the longevity of engineered barriers.
(f) The extent to which the geology provides physical and chemical stability.
(g) The extent to which the geology, hydrogeology and geochemistry tend to restrict the movement of radionuclides from the site to the accessible environment.

(h) The access routes that would allow waste packages and excavation equipment to be moved to the site; the site may also need services such as water and electricity.

Initial approach to site selection

5.23. In all cases, it is prudent to concentrate on the most robust solutions for achieving safety and on searching for sites with simple or well-understood geological and surface environments. The objective of this approach is to reduce the level of effort required to develop an acceptable disposal system in consideration of the characteristics specified above.

5.24. Typically, this information might include existing geological, topographical and hydrogeological mapping data, climate records and data from environmental surveys. In many regions, information in the form of detailed national surveys and maps may be scarce, which puts an even greater weight on finding geologically simple, stable regions. Much of this information would be readily available at an existing near surface disposal site. Further discussion of site characteristics is provided in Appendix IV.

Site characterization

Characterization activities

5.25. As expressed in the requirements for site characterization in Ref. [8], the overall aim of site characterization is to gain a general understanding of the site in terms of its regional setting, its past evolution and its likely future natural evolution over the time frame of the assessment (see para. 3.9). This will include, for instance, investigating the site characteristics listed in para. 5.22. This section considers the essential aspects of site characterization that should be carried out to obtain information for design and safety assessment purposes. As a minimum, these should include geology, hydrogeology, geochemistry, tectonics and seismicity, surface processes, meteorology, climate and the impact of human activities [9]. While the extent of the efforts needed for the characterization of these properties for large near surface and geological disposal facilities is considerable, given a relatively simple site and borehole disposal on a small scale, the amount of effort need not be too onerous, as explained below.

5.26. Once preferred areas or sites have been identified in the site selection process, the next steps would involve field activities, in particular the confirmation of the geological structure and hydrogeology down to the disposal zone by means of surface mapping. Preliminary geological, hydrogeological and hydrological models of the area would normally be developed from the mapping and from existing data and be used to identify the target disposal zone. The amount of information needed will depend on how complex the site is and on the margin of safety indicated by the post-closure safety assessment. Wherever possible, long term regional meteorological records should be consulted to give an indication of the range of conditions likely to occur in the future. These data may be used to estimate the susceptibility of a site to severe weather conditions (e.g. flooding) and also to estimate the recharge of groundwater from the site itself.

5.27. Following the surface mapping, normally at least one initial investigatory borehole would be drilled at the preferred site. This borehole should be designed to extract rock core to show the geological sequence down (if possible) to the base of the host formation. Rock samples should be characterized and preserved; others may, if necessary, be used to evaluate the radionuclide retardation properties of the rock (sorption, rock matrix diffusion). The investigatory borehole should also allow water sampling, ideally with flowmeter measurements, and standard geophysical logging.

5.28. For borehole disposal facilities of intermediate depth, the incidence of rock breakout in the wall of the investigatory borehole should be monitored, since breakouts could hinder the operation of the facility and might require the use of casing. In this regard, it may be helpful to measure rock stress.

5.29. In broad terms, drilling one or more investigatory boreholes has three main purposes:

(1) To gather sufficient hydrogeological data to construct a model of groundwater movement through the disposal zone and the surrounding rocks;
(2) To determine the nature of any chemical reactions (especially undesired reactions) between the engineered barrier system and the surrounding environment;
(3) To gather data relevant to the feasibility of constructing the facility and, for instance, the need for borehole casing.

5.30. Boreholes used for the purpose of site characterization should normally be sealed after use. Alternatively, if suitable, they may be used for waste disposal by becoming part of the facility.

5.31. Site characterization should also include characterization of the biosphere of the site and areas into which groundwater from the vicinity of the facility could discharge in the post-closure period. The information collected should cover land use, habits of the local population (especially the consumption of foodstuffs) and sources of drinking water. The nature of the present day biosphere will help to set the context for the biosphere model used in post-closure safety assessment. Similarly, data on food consumption are likely to be required for defining critical groups and estimating doses (e.g. Ref. [17]).

5.32. In post-closure safety assessment, the transport of radionuclides in groundwater (the 'groundwater pathway') is usually the dominant mechanism for the migration of radionuclides from the waste. Consequently, unsaturated sites or sites where groundwater movement is very slow (e.g. sites with rocks of very low permeability) may be advantageous in that, other things being equal, it will usually be easier to demonstrate compliance with a dose constraint or risk constraint than it would be for a site where groundwater movement were relatively rapid. Consequently, a saturated site in permeable rocks will generally require more effort to be expended on site characterization than would be the case for an unsaturated or very low permeability site. This subject is discussed at greater length in paras IV.21–IV.26 of Appendix IV.

Construction of the borehole disposal facility

5.33. Borehole construction should not proceed until a licence has been granted. This requires the regulatory body to review, assess and approve the impact of the proposed construction on radiological safety during both the operational and the post-closure periods. For example, the regulatory body should decide whether the proposed method of construction will be capable of fully delivering the proposed design in terms of borehole dimensions, borehole straightness, length of casing, capability to place a behind casing grout, etc. In addition, the regulatory body should decide whether the safety case adequately explains and justifies the actions to be taken in the event of abnormal events such as the loss of a drill bit, excessive water ingress or unexpected failure of the borehole wall. The safety case should describe measures for sealing 'failed' boreholes (i.e. boreholes where waste emplacement proves to be impracticable).

5.34. Whether the construction of a borehole disposal facility is straightforward or complex depends primarily on rock conditions, the borehole diameter and the depth. Clearly, though, facility construction should deliver the approved design while also preserving the post-closure safety functions of the geological barrier (see the requirements for geological disposal facility construction in Ref. [8]). This is most likely to be achieved when construction is straightforward (i.e. when rock conditions are amenable to the required borehole dimensions).

5.35. Construction should be accompanied by a planned programme of testing, commissioning and inspection (which is likely to include regulatory inspection). This programme should have the aim of demonstrating that construction of the facility is in accordance with the design and the associated technical specifications, and that the features revealed by its construction are consistent with what is known from the site characterization. This may require the removal and preservation of rock and groundwater samples.

5.36. Borehole construction should be carried out by suitably qualified and experienced personnel following previously approved written procedures [35]. These procedures should be derived from assessments of conventional construction safety and should be updated as practical experience is gained. Borehole construction records should provide a complete description of the history of construction, including when, how and by whom the borehole was constructed, its depth and diameter, the geological formations encountered and any non-compliances with regard to the construction procedures.

5.37. Construction of new boreholes could continue after the commencement of emplacement operations in boreholes already constructed. Such overlapping construction and operation activities should be planned and carried out to ensure both operational and post-closure safety following the specified licensing conditions.

5.38. Where boreholes pass through different hydrogeological regimes, drilling should avoid unnecessary disturbance. For instance, while the emplacement zone should avoid aquifers, it may be necessary to drill through an aquifer to reach the emplacement zone, and this will necessitate casing the borehole to isolate waste from the aquifer and to avoid the creation of pathways between different strata. Rock conditions and hydrogeology will vary from one borehole to another and there should be sufficient flexibility in the underground engineering techniques and/or the programme either to remediate marginally unsuitable boreholes or else to seal them off and close them without emplacing any waste. There are many ways in which a borehole can fail and contingency plans are needed to cover these eventualities.

Operation of the disposal facility

General

5.39. The operational phase of a borehole disposal facility includes commissioning activities, waste reception, waste emplacement, borehole backfilling, borehole sealing and site decommissioning and closure (the last two of these are discussed in paras 5.66 and 5.67). In addition, there can be various engineering tasks, including temporary storage or final conditioning of the waste. Operation of a borehole disposal facility will not, of course, be commenced until a licence has been granted. This requires that the regulatory body review and approve all aspects of operational safety to satisfy itself (i) that the design and the management procedures will allow the facility to be operated safely with regard to both workers and the general public, and (ii) that the operations will provide the post-closure safety functions on which the safety case depends (see the requirements for disposal facility operation in Ref. [8]). The operational safety case should include a radiological protection policy that describes how radiological hazards to workers and to members of the public are to be controlled under normal circumstances and what arrangements will be in place to deal with abnormal situations (e.g. emergencies). The safety case should also describe how the facility is to be commissioned and then operated. Only waste that complies with the waste acceptance criteria can be accepted for disposal. These issues are discussed in more detail below.

Radiological protection programme

5.40. International guidance on the engineering means and practical means of achieving radiological protection during the operational period is well established [14, 15, 38]. An essential component of this protection is the radiological protection programme (termed a radiological protection policy in the BSS [7]), which should document, with an appropriate level of detail:

(a) The assignment of responsibilities for occupational radiological protection and safety to different management levels, including corresponding organizational arrangements and, if applicable (e.g. in the case of itinerant workers), the allocation of the respective responsibilities between employers and the registrant or licensee;
(b) The designation of controlled or supervised areas;
(c) The local rules for workers to follow and the supervision of work;
(d) The arrangements for monitoring workers and the workplace, including the acquisition and maintenance of radiological protection instruments;

(e) The system for recording and reporting all relevant information relating to the control of exposures, the decisions regarding measures for occupational radiological protection and safety, and the monitoring of individuals;
(f) The education and training programme on the nature of the hazards and protection and safety;
(g) The methods for periodically reviewing and auditing the performance of the programme;
(h) The plans to be implemented in the event of intervention (e.g. accidents and emergencies and discovery of unforeseen chronic exposures);
(i) The health surveillance programme;
(j) The requirements for the quality management and process improvement.

5.41. The radiological protection programme is an essential part of the operational safety case and, as such, is subject to regulatory approval. Translation of the programme into action requires the employment of suitably qualified and experienced personnel.

Recruitment and training of personnel

5.42. Well before commencing operation, the operator should determine the organization's personnel requirements in terms of numbers, responsibilities and expertise, and then proceed to recruit and train suitably qualified persons. The training programme should identify the activities that are significant for safety and should provide the knowledge and practical experience necessary for these activities; it should also foster the development of a safety culture. The training should give operational staff a high degree of awareness of the design features of the repository that are significant for safety. The training programme should be updated in the light of experience and staff should be retrained as necessary.

5.43. Technical expertise is likely to be needed in operational radiological protection, remote handling, waste packaging, waste transport, borehole construction and closure, and safety assessment.

Commissioning

5.44. The operational techniques should be tested and confirmed, especially those used for putting in place the engineered barriers and for emplacing the waste packages in the borehole. This may be done through the use of an inactive test facility and, later, through on-site commissioning tests.

5.45. For deeper, smaller diameter boreholes, where access and retrieval of waste packages are more difficult, consideration should be given to ensuring that:

(a) The possibility of dropping waste packages is very unlikely.
(b) Waste packages are correctly positioned in the facility.
(c) Waste packages are correctly backfilled.

Written procedures

5.46. The operator should prepare a set of rules, incorporating limits, controls and conditions derived (mainly) from the operational and post-closure safety assessments, to ensure that the facility is operated safely and in compliance with the conditions of the licence and national regulations. These rules should reflect consideration of:

(a) Protection criteria for occupationally exposed workers and members of the public in normal operation and accidents;
(b) The limiting assumptions used in the safety assessment.

5.47. To ensure that identified controls are in place and that limits and conditions are observed, operations impacting on safety need to be specified in written procedures and instructions [8, 35]; the operator is also responsible for ensuring that workers follow these procedures and instructions carefully. Operating procedures are derived from the technical specifications for operations which, in turn, are based on the operational safety assessment. The overall aim is to provide safety by ensuring that the work that is actually done during operation is adequately covered by the safety assessment and the safety case and that it achieves the design aims for operation. Demonstration of this achievement should be provided by means of inspection, auditing and record keeping (see below). It is also important that proper attention be given to safety during the modification of equipment or operating procedures. Formal change control procedures should be used (see para. 4.11).

5.48. The operator should also establish procedures for prescribed actions in the event of (i) emergencies or non-routine occurrences (e.g. jamming of waste packages in boreholes) and (ii) receipt of waste that does not conform to the waste acceptance criteria. The procedures should also specify when reports should be made to the regulatory body.

Emplacement strategies

5.49. The operation of borehole disposal facilities may be performed on a continuous basis or a campaign basis or a combination of the two. With continuous operation, packages are placed in the borehole disposal facility as they arise and the operator may, therefore, need to exercise operational control over the site for several years. Campaign operation involves the accumulation of waste in stores until there is sufficient waste to be disposed of in a new borehole. This provides 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. Provided that waste packages are weather resistant, they could be stored in a secure, access controlled, open air compound. It is likely that continuous operation would be most appropriate in the case of large capacity boreholes where quite extensive storage facilities would be needed. In this case, rainwater and surface water should be prevented from entering the borehole, which should be fitted with a secure cover when operations are pending.

5.50. In facilities where different types of waste are to be disposed of, it is sometimes suggested that packages containing high activity or long lived waste should be placed in the bottom part of the borehole and packages containing low activity, short lived radionuclides at the top. This could improve post-closure safety and limit the consequences of human intrusion. However, such emplacement strategies might be difficult to operate in practice, requiring longer storage times, more complicated on-site storage facilities, greater assurance regarding the location of individual waste packages and, probably, higher operator doses. In general, it is preferable for facility designers to aim for a simple, robust scheme in which any waste packages can be placed in any borehole in any order. It is recognized, of course, that this may not always be possible, especially for boreholes where the waste emplacement zone comes close to the surface and where there are significant numbers of high intensity sources to be disposed of.

Backfilling boreholes

5.51. Following waste emplacement, there will usually be a need for the borehole to be backfilled. Materials that could be used for backfilling include cement, bentonite slurry, or a loose fill of bentonite granules, sand and so on. It may be necessary to design and to demonstrate measures to reduce the possibility of leaving voids after backfilling. These could include backfilling in stages.

5.52. For deeper boreholes, backfill would be introduced following the emplacement of individual packages. In this case, it may be possible to use pressure grouting to introduce the backfill, provided that the borehole is uncased (or screen cased). When boreholes of this type are fully cased and sealed at the bottom, it will be necessary to rely on gravity, although backfill placement could be assisted by pumping out the air beforehand.

Sealing of boreholes

5.53. Following waste emplacement and backfilling, the operator will seal each borehole following the method prescribed in the licence and the safety case. This activity, which may be overseen by the regulatory body, will place the borehole into its final configuration and preserve the safety functions on which post-closure safety depends (see the requirements for geological disposal facility closure in Ref. [8]). Boreholes may be sealed and closed individually or collectively at the end of a disposal campaign. If seals are not put in place for a period of time after the completion of waste emplacement, then the implications for operational and post-closure safety should be considered in the safety case. Likewise, the implications of any unexpected postponement of sealing should be considered.

5.54. In the case of intermediate depth boreholes of smaller diameter, sealing requires sections above the disposal zone to be filled with a low permeability material to prevent shallow groundwater penetrating the waste, or to prevent pore waters that are saturated with waste from moving upwards from the disposal zone. Standard borehole cementing and sealing approaches are likely to be appropriate, with the precise technique depending on the size of the hole, whether it is cased or not, and the geology. Where a borehole is uncased, a seal, at least, should be placed within the host rock formation. In general, it will be beneficial to remove the casing above the disposal zone since this will allow the installation of a monolithic seal grouted into the adjacent rock and will remove a potential leakage pathway to the surface along degraded casing or poor grout-to-casing bonds.

Inspection and review

5.55. Safe operations should be achieved through the application of recognized technical and managerial principles [35]. Thus, the licence to operate may require the operator to conduct periodic reviews covering issues such as quality assurance audits, operating conditions, environmental sampling and analysis, occupational health and safety, and maintenance of records. The results of these reviews should then be submitted to the regulatory body.

5.56. The regulatory body may also carry out independent audits, inspections and reviews to satisfy itself that appropriate technical and managerial principles are being effectively applied. Corrective actions and repeat inspections should be applied when this is found not to be the case.

Records

5.57. An important operational requirement is the recording of relevant information, as stipulated by the regulatory body. With respect to the waste itself, much of this information will have been obtained from the waste generators and will form part of an already existing national waste inventory. Each waste package should have a unique identification. For each waste package, information should be compiled on its principal characteristics (e.g. origin of the waste, radionuclide content of the package, method of encapsulation, materials of the waste container, method of closure).

5.58. Operational records should describe when, how and by whom an operation was carried out and, especially, any non-compliances with the operating procedures. When waste is emplaced, for instance, the position of the waste package should be recorded (e.g. the number and location of the borehole and the position within the borehole). Processes such as backfilling and sealing should be similarly recorded.

5.59. Consideration should be given to the form of the records to ensure that information is available when needed without interruption or loss. This information will form part of the safety related information archived for the benefit of future generations (see the section on post-closure institutional controls beginning at para. 5.68). Further information on the maintenance and preservation of records is provided in Ref. [35].

Waste acceptance criteria

5.60. A key component of the assemblage of limits, controls and conditions to be applied by the operator is the waste acceptance criteria. No waste package can be accepted for disposal unless it is compliant with the waste acceptance criteria, which aim to ensure that waste packages are consistent with the safety case, especially the safety assessments for transport, predisposal operations, disposal operations and post-closure. Waste acceptance criteria are usually developed by the operator and approved by the regulatory body, although sometimes the regulatory body may specify criteria. Consequently, waste acceptance criteria are usually used to ensure that waste packages are compatible with all stages of waste management through the imposition of a series of technical and management controls. Waste acceptance criteria are a safety relevant component of the facility design and they should therefore be subject to a change control process that entails internal safety reviews and regulatory scrutiny.

5.61. In the early stages of a programme for the development of a facility, not all the details of the safety case (e.g. the site) will have been settled and, in principle at least, this could make it difficult to determine the waste acceptance criteria. In practice, this rarely seems to be a significant problem, since several IAEA Member States are already conditioning and packaging waste in the absence of a known disposal site. This is possible because most disposal concepts are specifically designed for the disposal of waste inventories that, from the outset, are known to contain many kinds of waste, some of which will already have been packaged. This prevents the waste acceptance criteria from being drawn too narrowly. Consequently, provided that there is a good understanding of the range of wastes that should be disposed of, it should be possible, even at an early stage in the programme, to formulate waste disposal criteria that are sufficiently flexible for a wide range of wastes to be accepted. Nonetheless, close attention should be paid to waste that was conditioned and packaged prior to the adoption of waste acceptance criteria and the associated quality management regime. For the small number of waste packages that cannot be accepted for disposal, repackaging may be an option.

5.62. Waste acceptance criteria commonly impose:

(a) A limitation to the use of only solid waste forms;
(b) Limits on the radionuclide content, fissile content, total activity and radiation level on the surface of a package, as well as total limits for the borehole and the entire facility;
(c) Waste forms with stable chemical and physical properties (e.g. no putrescible material);
(d) Allowable and non-allowable encapsulation materials;
(e) Limits on gas release rates;
(f) Limits on the weight and physical size of waste packages;
(g) Specifications for waste containers (e.g. acceptable materials, dimensions, weld testing);
(h) Management systems for waste characterization, packaging, handling and storage.

5.63. The existence of waste acceptance criteria implies a need for waste characterization, and this is usually the responsibility of the waste generator, made on the basis of guidance provided by the operator and approved by the regulatory body. Modelling of waste behaviour and/or testing may also be required to demonstrate compliance with the waste acceptance criteria. Typically, waste packages are tested for their physical and chemical stabilities under disposal conditions by the use of laboratory simulations. Similarly, tests may be used to examine the performance of waste packages in accident conditions or abnormal conditions. For well-known materials, such as “Grade 316 stainless steel” and “Ordinary Portland cement”, most of the relevant information may already be available. It should usually be the responsibility of the waste generator to demonstrate compliance with the waste acceptance criteria and to provide this information to the operator.

5.64. Procedures should be in place that describe the actions to be taken on receipt of waste that does not conform to the waste acceptance criteria. Depending on the severity of the non-conformance, the actions may range from notification to the waste packager and remediation on-site to enforced shutdown of the production process for waste packages. For significant non-conformances, the regulatory body should be notified.

5.65. Sealed sources that contain radionuclides in category I and II quantities (particularly radionuclides of longer half-life, such as ^{90}Sr, ^{137}Cs, ^{238}Pu and ^{241}Am) [39] should not be disposed of in near surface boreholes unless there are additional physical or administrative controls in place to prevent or reduce the likelihood of intrusion and/or mitigate its consequences. Otherwise, intermediate depth disposal should be considered.

Decommissioning of buildings and closure of the disposal facility

5.66. When all boreholes are backfilled and sealed, the site itself should be closed. Regulatory approval for decommissioning and site closure (which are regarded as operational activities) will require the submission of an updated safety case using current data to demonstrate that the required post-closure performance will be achieved. The safety case should also include detailed plans for both decommissioning and closure. These plans should describe the decommissioning activities (e.g. site surveys, decontamination and removal of any redundant buildings and equipment, site remediation, final survey to confirm any necessary site cleanup and transfer of documents to other premises) and demonstrate that the closure activities will not impair the post-closure performance of the facility. An IAEA technical report discusses the decommissioning of small facilities [40].

5.67. The closure plan should also describe any arrangements intended for the post-closure institutional phase. These arrangements should include a system for archiving and preserving records. They might also include, especially in the case of facilities that extend to within 30 m of the surface, control of access to the site, maintenance of site security, a surveillance programme and a radiological monitoring plan. In each case, the closure plan should identify the organization responsible for conducting these activities. Ownership of the site should be clearly and appropriately allocated. When the closure operations have been satisfactorily completed, the period of post-closure institutional control can begin. Depending on the regulatory framework and the conditions of the licence, this may or may not require separate regulatory approval.

Post-closure institutional controls

5.68. Institutional control is defined as any form of institutional activity, from oversight by international agencies and national governments to very specific activities such as environmental monitoring. It is generally expected that institutional controls will assist with the societal acceptability of the disposal. Institutional controls are generally classified into 'active' and 'passive' controls. Active institutional controls include:

(a) Maintaining signs, fences and guards at sites to prevent unauthorized access and intrusion by animals.
(b) Maintaining access, maintaining the grounds, weed control, etc.
(c) Monitoring and surveillance (see paras 5.74–5.80).
(d) Performing any remedial work that may become necessary, for instance, on the basis of the monitoring and surveillance programme.

Passive institutional controls include:

(a) Long term markers;
(b) Restrictions on land use and ownership;
(c) Preservation of records;
(d) Financial assurances.

5.69. Whether the duration of the institutional control period is defined by law or established on a case by case basis through the approval of closure plans, it should be specified in the site closure plan (see the requirements concerning post-closure and institutional controls in Ref. [8]) and justified by reference to its potential future hazard (e.g. the rate of radioactive decay of the waste, human intrusion scenarios or historical experience of the retention of information). Institutional control periods, often of the order of 100–300 a, are frequently part of the safety concept for many near surface disposal facilities associated with nuclear power programmes. The site closure plan, including any newly proposed institutional control period, should require the review and approval of the regulatory body before being implemented.

5.70. The post-closure arrangements should be documented and should identify the institutional controls that are to be provided during the institutional control period, who is responsible for providing them and how long each control will stay in place. Earlier removal of any institutional controls should need the prior approval of the regulatory body.

5.71. In general, small scale borehole disposal facilities at intermediate depth represent lesser hazards in terms of the surface 'footprint', proximity of the waste to the surface and the amount of waste disposed of. The safety of the facility will not depend on institutional controls and quite short periods may be justifiable, so land could soon be returned to local community use with, possibly, restrictions on ownership and use within a period of a few years.

Information to be archived

5.72. Passive institutional controls can help to maintain knowledge of the facility's location and characteristics within societal institutions. Information that should be preserved with respect to a borehole disposal facility is primarily:

(a) Its precise location;
(b) Its geology, geochemistry and hydrology derived from site characterization data (paras 5.25–5.32);
(c) Design details of the facility, including descriptions of, for example, the backfill, casing and seals (paras 5.18, 5.19, 5.51–5.54);
(d) Detailed descriptions of the waste packages, including waste origin, radionuclide content, encapsulation matrix and containers (paras 4.22–4.24, 5.18, 5.19);
(e) Descriptions of the construction and operation, including dates and details such as measured water inflows to boreholes and, especially, any non-conformances and actions taken to rectify them (paras 5.33–5.59);

(f) The facility safety case (Appendix III) and supporting information (e.g. from site characterization (paras 5.25–5.32));
(g) A description of the post-closure arrangements (para. 5.68);
(h) Outputs from the surveillance and monitoring programme, including baseline surveys (paras 5.74–5.80).

5.73. Such information should be retained for as long as possible to provide a basis for any future decisions concerning the site. This may be most easily done by making use of national archives. Long term site markers may also help, although consideration should be given to their possible implications for security.

Surveillance and monitoring programmes

5.74. A programme of surveillance and monitoring should form part of the safety case and should commence before a disposal facility becomes operational — usually during the site characterization programme. As the disposal programme moves from one phase to the next, the objectives of the surveillance and monitoring programme will change and additional surveillance and monitoring activities will be added [41]. Some of these activities may continue through into the period of post-closure institutional control. Through the various phases of development of the facility, the surveillance and monitoring objectives should be set to allow the surveillance and monitoring programme to contribute to the building of confidence in the safety case by testing assumptions and demonstrating compliance. For example, Ref. [1] lists the main objectives of the post-closure surveillance and monitoring phase as follows:

(a) To show compliance with reference levels established by the regulatory body for the purpose of ensuring the protection of human health and the environment;
(b) To confirm, as far as possible, relevant assumptions made in the safety assessment;
(c) To provide indications of any malfunctioning of the containment leading to unpredicted releases of radionuclides;
(d) To provide reassurance to concerned persons living in the vicinity of the waste disposal facility.

5.75. An important principle of the surveillance and monitoring of facilities is that the programme should be designed and implemented so as not to reduce the overall level of post-closure safety (see the requirements concerning monitoring programmes in Ref. [8]). The surveillance and monitoring programme should not place an undue burden on the operator by being too elaborate; for a small scale disposal facility especially, the arrangements may be relatively simple. Appendix V provides such an example.

5.76. As part of site characterization, a baseline of environmental levels, radiation levels and activity concentration levels should be established for the purpose of subsequently determining the changes (if any) brought about by the emplacement of the waste. These data may include surface radiological data such as gamma radiation fields, the radionuclide content of airborne dust and the radionuclide (including radon) content of the soils, water and air on and around the site. These data and their current impact on humans should be used to gain an understanding of radionuclide transfer pathways, especially in areas where groundwater from the vicinity of the facility could discharge. The monitoring should also cover wider environmental information such as that on the local ecology, chemical pollutants, population density and habits, local agriculture, and natural and artificial features of the environment that might affect radionuclide transfer pathways [41].

5.77. The results of predisposal surveillance and monitoring will assist in building confidence in the safety and post-closure performance of the borehole disposal facility and will aid in decisions on its future development. The monitoring programme may also be useful in creating the geosphere and biosphere models to be used in the post-closure safety assessment.

5.78. Borehole disposal facilities with boreholes less than 30 m deep should be subject to post-closure surveillance and monitoring of a similar nature to that proposed for near surface disposal facilities [42]. Facilities containing intermediate depth boreholes in saturated environments may be monitored for potential releases through the nearby water bearing horizons, even if releases of radionuclides are anticipated to occur only in the distant future. Where monitoring boreholes are used, they should be sealed after use.

5.79. The regulatory body should provide, if necessary, guidance on the establishment of a surveillance and monitoring programme to be used (i) to demonstrate compliance with the regulatory constraints and any other licence conditions, (ii) to monitor any migration of radionuclides to the environment and (iii) to assess the environmental impact of construction, operation, closure and post-closure activities. The operator would normally carry out this programme and would take the necessary actions to ensure that the requirements established by national authorities are met. The regulatory body should:

(a) Check the surveillance and monitoring data provided by the operator;
(b) Regularly review surveillance and monitoring arrangements, including arrangements for emergency monitoring;
(c) Audit the management systems;
(d) Provide evidence that can satisfy the public that there are no unauthorized sources of exposure.

5.80. In addition, the regulatory body may carry out an independent surveillance and monitoring programme.

Accounting and control systems for nuclear material

5.81. Systems for accounting and control of nuclear material have been developed to provide for the accountability of nuclear material so as to detect, in a timely manner, its diversion to unauthorized or unknown purposes in the short and medium terms. As presently organized, systems for accounting and control of nuclear material rely on active surveillance and controls. The discussion of the requirements in paras 3.79–3.81 in Ref. [8] makes it clear that for some radioactive waste, particularly that containing fissile material such as spent nuclear fuel, certain requirements on accounting and control of nuclear material have to continue, even after the fuel has been sealed in a geological disposal facility. Possible malicious uses of other (non-fissile) material do not fall within the system for accounting and control of nuclear material.

5.82. Borehole disposal is designed primarily to dispose of small volume waste (e.g. disused sealed sources), particularly when they arise in States that lack well-developed systems for dealing with high level radioactive waste deriving from the nuclear fuel cycle. Such waste may pose a potential security risk, but, because of its low fissile content, will not fall within the system for accounting and control of nuclear material.

Management systems

5.83. Management systems are applicable to any organization, but, in the context of radioactive waste management, they apply most importantly to the operator. This subject is discussed at greater length in Appendix VI.

6. IMPLEMENTATION OF THE SAFETY STRATEGY FOR EXISTING BOREHOLE DISPOSAL FACILITIES

6.1. Standards, procedures and practices all change over time and therefore some older borehole disposal facilities may not be consistent with the safety guidelines presented in this Safety Guide. Specifically, human intrusion scenarios at some older borehole disposal facilities could lead to doses in excess of 10 mSv/a, at which level remedial action should be considered in intervention situations. Intrusion in some facilities may even lead to doses exceeding 100 mSv/a, a generic reference level above which intervention should be considered almost always justifiable. This section considers past practices in borehole disposal from a regulatory perspective. 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 [1] requires contracting parties to report on past practices and possible interventions. Furthermore, for both closed facilities and operating facilities, the periodic reassessment of safety constitutes good practice.

6.2. The purpose of a safety reassessment for an existing waste disposal facility should be:

(a) First, to assess whether the facility satisfactorily provides protection from radiation for future generations in accordance with the Fundamental Safety Principles [13] and the requirements of the BSS [7];
(b) Second, if appropriate standards are not met, to determine whether there is justification to intervene at the facility and to retrieve the waste or take other corrective action.

6.3. 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 should be emphasized that the application of these criteria to possible future doses is far from straightforward. Intervention should be based on justification and optimization [8]. Put succinctly, any corrective action should do more good than harm.

6.4. In the current context of borehole disposal, this means that national authorities, which are responsible for taking such decisions, should balance the possible future risks to individual members of the public against actual risks to the workers who would be associated with the intervention. If the approach is applied to existing borehole disposal facilities, it is likely to lead to a situation where one of the following options should be chosen.

Option 1: Carrying out additional site studies and applying justified corrective actions

6.5. The simplest corrective action at an existing disposal facility will, typically, depend on some form of institutional control (e.g. restrictions on access) and will therefore only be effective so long as the period of active institutional control continues. Such controls could be accompanied by other measures, such as the use of anti-intrusion barriers. Where the radionuclides in the waste are mostly short lived, such approaches will usually be adequate. However, where the radionuclides are long lived (and especially where there is significant in-growth), such corrective actions will not alter the long term dose projections for the facility.

6.6. A slightly different approach would be to focus the site characterization and data collection efforts to address issues raised by the safety assessment, in the expectation that new data would allow conservatisms in the safety assessment to be reduced so as to bring the dose projections within the acceptable range. However, the removal of conservatisms usually leads to increased complexity in modelling and data requirements. This is, nonetheless, still likely to be the most cost effective approach.

Option 2: Retrieving the waste

6.7. In evaluating the advisability of this option, several issues should be considered. First, the optimization of doses should be considered. This means that doses to workers incurred during the retrieval of any waste should be considered and these should be optimized against the possible doses associated with leaving the waste in place. While a number of Member States have carried out, or are planning, the retrieval of waste from certain facilities, there is, at present, no clear consensus on an appropriate approach to carrying out such an optimization. In addition, if waste were retrieved, it would eventually have to be disposed of somewhere. Such disposal would inevitably lead to potential exposures that should be accounted for in the optimization assessment. Finally, if the waste were to be retrieved, the associated activities would have to be carried out safely and in conformity with the BSS [7].

Option 3: Accepting possible risks associated with the existing situation

6.8. 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 on the basis of a careful assessment of the 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.

6.9. In the end, a decision to carry out an intervention should be endorsed by the regulatory body, which should take into account the following aspects:

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

Appendix I

REGULATORY INSPECTION PLAN FOR A BOREHOLE DISPOSAL FACILITY: ITEMS THAT MAY BE SUBJECT TO INSPECTION

I.1. Structure and organization of the operator:

(a) General management of the organization;
(b) Appropriate allocation of responsible experts (in radiological protection, security, waste acceptance, etc.);
(c) Job descriptions;
(d) Arrangements for reporting to the competent regulatory bodies.

I.2. Operational procedures:

(a) Characterization and control of received waste;
(b) Radiological protection programme;
(c) Environmental monitoring programme;
(d) Personnel monitoring programme;
(e) Plans and programmes for training and qualification of personnel;
(f) Emergency plan (on-site and off-site);
(g) On-site handling procedures;
(h) Procedure for on-site storage of waste;
(i) Procedure for the management of waste that is non-compliant with safety requirements, waste acceptance criteria and other limits, controls and conditions;
(j) Internal audit and inspections;
(k) Reporting and notification of competent authorities;
(l) Quality management programme.

I.3. Actual status of the facility:

(a) Design of the facility and waste packages in compliance with the authorized safety case;
(b) Security and access to the facility (register of people able to access the site);
(c) Personnel monitoring equipment;
(d) Environmental monitoring equipment;
(e) Application of operational procedures;

(f) Register of received waste on the site;
(g) Record of periodic individual monitoring;
(h) Register of disposed waste;
(i) Record of periodic on-site and off-site environmental monitoring;
(j) Testing of the on-site (and where appropriate the off-site) emergency plan;
(k) Recording and evaluation of feedback from operational experience.

I.4. Compliance with licensing conditions:

(a) Control over waste acceptance criteria and limits, controls and conditions on the basis of the safety case;
(b) Control over compliance with additional conditions for authorization(s);
(c) Change control procedures.

I.5. Fulfilment of prescriptions and recommendations from previous inspections.

Appendix II

THE STEP BY STEP APPROACH

II.1. In consideration of the lower level of hazard associated with wastes that might be disposed of in a small scale borehole disposal facility, the application of the step by step approach to the development of a borehole disposal facility should be relatively simple. It should, nonetheless, still aim to provide a framework in which confidence in both feasibility and safety is progressively increased as the development proceeds. This may be done by breaking down the development programme and the licensing process into a series of steps that allow stakeholder inputs at key decision points.

II.2. The framework for a small scale borehole disposal facility could, for example, consist of two steps with two decision points, both of which could be preceded by public consultation:

Decision 1 would adopt borehole disposal as the favoured solution and put in place the required legal and regulatory framework. A licence would allow step 1, predisposal activities, to proceed, including:

(a) Definition of the inventory for disposal;
(b) Formulation of a conceptual design;
(c) Generic assessment of safety;
(d) Waste conditioning and packaging;
(e) Site selection following predetermined criteria and process;
(f) Characterization of the most favoured site;
(g) Development of a site specific design and safety assessment;
(h) Recommendation of the most favoured site.

Decision 2 would approve the most favoured site and site specific design and safety assessment. A licence would allow step 2, waste disposal and closure, to commence, including:

(a) Borehole construction;
(b) Waste emplacement;
(c) Borehole sealing;
(d) Decommissioning and closure of the disposal facility;
(e) Commencement of any post-closure institutional control period.

II.3. A larger scale programme of disposal of radioactive waste in boreholes would usually require additional steps to be introduced. For instance, a more gradual and consultative approach to site selection may be appropriate. Another consideration is that a larger scale disposal programme may require the disposal site to remain operational for a period of decades. In this case, it may be appropriate to approve the site but to require each new tranche of boreholes to be licensed separately. This would allow the safety case to be updated and subjected to regulatory review in the light of new data. Finally, with a decades long operational period, it may be convenient to put decommissioning, closure and commencement of post-closure institutional control into a separate sequence that requires a separate licence.

II.4. A more detailed action plan for disposal in a borehole is suggested in Ref. [3].

Appendix III

SAFETY CASE AND SAFETY ASSESSMENT FOR BOREHOLE DISPOSAL FACILITIES

Preparation of the safety case and safety assessments

III.1. The first iteration of the safety case will be prepared early in the development process for the facility and, if no site has been identified, it will be generic. An important early task is to identify the intended inventory for disposal since this will determine the overall size of the programme, including the extent of the radiological protection measures that should be taken during transport and operation and the level of isolation and containment required in the post-closure period. Ideally, the inventory for disposal should include all the sources or waste types that are expected to arise. The safety case will then be progressively refined as the site and details of the design are decided, finally allowing the preparation of a site specific safety assessment.

Post-closure safety assessment

III.2. An important component of the safety case is the post-closure safety assessment, which should aim to demonstrate that the ultimate goal of disposal — post-closure safety — will be achieved. A methodology for the assessment of both operational and post-closure safety of near surface disposal facilities has been developed by the IAEA's ISAM project on International Safety Assessment Methodologies for Near Surface Disposal Facilities [28]. The methodology has been applied illustratively to a borehole disposal facility as part of the ISAM project and has also been used in a generic assessment of the African Regional Cooperative Agreement for Research Development and Training Related to Nuclear Science and Technology Borehole Disposal Concept [43]. The ISAM approach provides a comprehensive framework for post-closure safety assessments, the importance of the context of safety assessment being stressed — the underlying reasons for carrying out an assessment — in helping to define such things as the scope of the assessment and how it is to be documented. The key components of the methodology are illustrated in Fig. 3.

III.3. A disposal facility may be affected by a range of possible evolutions and events, some of which will be more likely than others. In assessing post-closure safety, common practice is to construct a design evolution scenario for the

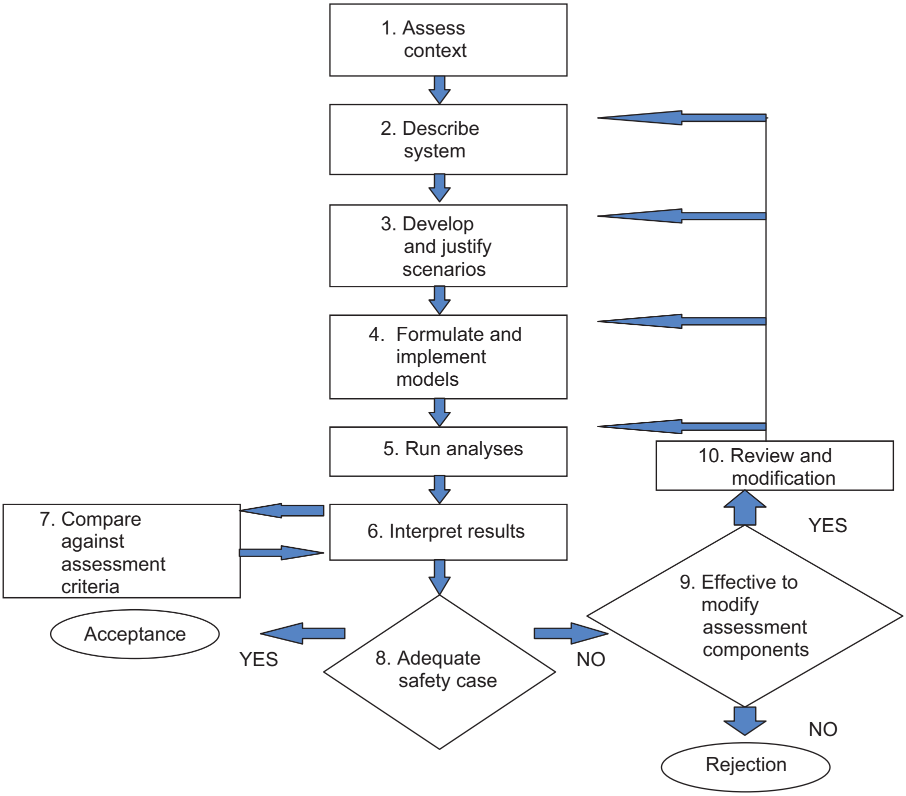

FIG. 3. The ISAM approach for post-closure safety assessment.

facility, which is the scenario that is thought to have the greatest likelihood of occurring. The design evolution scenario should incorporate all the natural processes and natural events (Table 2) that might reasonably be expected to give rise to radiation exposure of the public. Some possible design evolution scenarios are indicated in Table 3. For the design evolution scenario, estimates of long term dose (and the corresponding risk) can then be made by assuming that humans will be present and that they will make use of local resources that may contain radionuclides originating from the waste. A methodology for doing this, developed alongside a series of reference biospheres, has been put forward in the IAEA BIOMASS project [17].

III.4. Variants of the design evolution scenario in which there is a reduced system performance should be explored (Table 2) with the aim of evaluating the importance of the various barriers (remembering that the overall performance of the disposal system should not be unduly dependent on a single barrier or function). These variants might arise, for instance, from alternative interpretations of the hydrogeology or by assuming that some waste containers are faulty. A common way of investigating these variants is through the use of a probabilistic approach to post-closure safety assessment.

III.5. Less likely scenarios (Table 2) are triggered by a subset of features, events and processes sometimes termed external features, events and processes. These less likely scenarios should also be investigated. Typically, they include:

(a) Unlikely natural events that significantly disrupt the facility (e.g. meteorite impact);
(b) Human intrusion.

III.6. Less likely scenarios should be assessed by means of illustrative 'what if' calculations. Here, the aim is to judge the robustness of the system to external features, events and processes. These calculations may point out a need for additional research or even design changes to ensure that if such external features, events and processes do occur, they do not lead to widespread loss of safety functions. In assessing the risk that arises from human exposure to radiation in less likely scenarios, the probability of occurrence of the scenario should be taken into account.

III.7. Human intrusion studies should be focused on any disruption to the engineered and natural barriers caused by inadvertent human intrusion and the subsequent effect of this disruption in terms of increased dose to the general public.

III.8. As indicated by the typical scenarios shown in Table 3, for near surface borehole disposal facilities (i.e. where the waste is placed less than 30 m below the surface), the types of inadvertent human intrusion that might be envisaged for a borehole disposal facility include:

(a) Excavation of deep building foundations, deep cuttings for roads or railways, cut and cover tunnel construction, standard tunnelling, open cast mining, etc. (in general, these would result in high levels of dilution owing to the large volume of uncontaminated material that would be involved);
(b) Exploratory drilling for water or natural resources, which may be important after the physical containment has been breached.

TABLE 2. EXAMPLES OF SCENARIOS AND CORRESPONDING DOSE/RISK TARGET LEVELS

Scenario	Design evolution scenario[a]	Variant scenario with reduced system performance	Illustrative, less likely scenarios			
			Natural disruptive events	Environmental change	Societal change	Human intrusion
Scenario description	Anticipated system performance, including expected rates and levels of barrier degradation	Includes rates and levels of barrier degradation considered to be unlikely	Events considered to be very unlikely but with potentially serious consequences for safety	Global or regional climate change leading to different ecology, change in sea level	Societal change resulting from war, famine, collapse of societal infrastructure	Premature barrier failure caused by human intrusion
Examples	Container degradation at expected rate; expected range of times for groundwater to return to the biosphere	Premature barrier failure, so the time needed for groundwater to reach the biosphere is significantly less than modelled	Seismic events, volcanism, meteorite impact	Premature ice age caused by interruption of the Gulf Stream	Hunter–gatherer lifestyle Subsistence community	Exploratory drilling Deep water abstraction
Reference dose/risk target level[b]	Annual dose <0.3 mSv	Annual risk $<10^{-5}$	Annual risk $<10^{-5}$	Annual risk $<10^{-5}$	Annual risk $<10^{-5}$	Annual dose <10 mSv

[a] There could be more than one design evolution scenario if, for instance, different climate sequences are thought to be equally likely.

[b] It should be understood that the crucial issue for safety is design optimization. Target dose/risk levels are ancillary to this. Risk constraints apply to the four middle columns because this allows the probability of the event to be taken into account.

TABLE 3. EXAMPLES OF DIFFERENT ASSESSMENT SCENARIOS FOR NEAR SURFACE BOREHOLES AND BOREHOLES AT INTERMEDIATE DEPTH[a]

Design evolution	
Residence on the waste Farming on the waste	near surface borehole
Contamination of aquifer/drinking well/agricultural well Contamination of surface water bodies Contamination of near surface groundwater	borehole at intermediate depth
Natural disruptive events	
Erosion Seismicity Meteorite impact	near surface borehole and borehole at intermediate depth
Human intrusion	
Excavation (e.g. road building) Tunnelling	near surface borehole
Exploratory drilling	borehole at intermediate depth

[a] For further information see, for example, Ref. [26] and the Annex.

III.9. As mentioned previously (para. 4.28), in the case of near surface boreholes, it is reasonable for the safety case to claim credit for active controls exercised during the post-closure period. In such cases, the controls and the period of time over which they are assumed to be effective should be specified as conditions of the relevant licence or authorization [9].

III.10. For borehole disposal facilities where the waste is deeper than the 30 m 'normal residential intrusion zone' [12], it is likely that the only mode of potential human intrusion would be exploratory drilling (Table 3).

III.11. The outputs from models used for post-closure safety assessment will inevitably be subject to greater uncertainty since the results are projected further into the future. Here, other arguments may also be used to demonstrate safety. They may, for example, be based on bounding analyses and comparisons with natural phenomena such as the behaviour of naturally occurring radioactive deposits.

Documentation of the safety case and safety assessments

Scope

III.12. A safety case should use sound science and engineering to describe the level of protection to be provided. It should address all aspects of safety: operational safety, post-closure safety, plus, if these are the responsibility of the operator, predisposal activities and transport. This is carried out by performing safety assessments. As stipulated by the requirements concerning documentation of the safety case and safety assessments in Ref. [8], the safety case is also required to describe the managerial (e.g. quality management) arrangements and other limits, controls and conditions (e.g. waste acceptance criteria) that will be applied to ensure that the relevant safety standards will be met. It should also address security. In the absence of an overarching environmental impact assessment, it could also be used to examine the full range of options available at that stage of the decision making process and also non-radiological environmental impacts.

III.13. The scope of the safety case should cover the design of the disposal facility, its location and how the waste is to be transported there, and how the facility is to be operated, closed and managed during any period of post-closure institutional control. A more detailed list of issues that should be covered by the safety case may be extracted from paras 5.14–5.83. Finally, the safety case should present the arguments for safety during the post-closure period by means of a post-closure safety assessment.

III.14. The volume of information and the degree of uncertainty associated with it will change as the facility development programme moves forward. In the early stages, when a site has not been selected, for instance, some of the information will be very uncertain. The safety case should identify key uncertainties, explain how they affect the safety case and describe further work intended to resolve them.

III.15. Throughout the development programme, an important function of safety assessment is to identify these key areas of uncertainty (i.e. those that impinge most directly on the calculated dose), so that activities such as site characterization and research can be properly targeted. This is often done by means of sensitivity studies. Sometimes, these key uncertainties will relate to individual parameters used in safety assessment (e.g. the inventory of a specific radionuclide). More often, the key uncertainty will be related to a combination of models and parameters. For example, the anticipated container lifetime will depend not just on material properties and environmental conditions, but on the method (i.e. the model) used to extrapolate short term laboratory data to the long timescales needed for safety assessment. Similarly, the time taken for a specific radionuclide to migrate through the geosphere will depend on hydrogeological and other models as well as on parameters such as the sorption coefficient. Here, improvements to the safety assessment can be obtained by means of additional data and model refinements. In many cases, the analysis of new data will itself suggest ways of improving a model.

III.16. In summary, the safety case should describe how the facility will meet the various safety objectives and criteria discussed in Section 3. This entails explaining:

(a) How, and to what degree, workers and the general public will be protected during site operations (including abnormal (i.e. accident) conditions) and during predisposal activities and the transport of waste to the site, if these are the responsibility of the operator;
(b) How the facility design and the site location will provide isolation and containment during the post-closure period, with account taken of the important uncertainties, so that radiological impacts for the critical group are within the defined dose limits and risk limits.

Level of detail

III.17. A safety case and the accompanying safety assessments should be written so as to be intelligible to the audiences to whom they are addressed. Beyond this, the requirements concerning documentation of the safety case and safety assessments in Ref. [8] demand that, at each step, the safety case should be sufficiently detailed and comprehensive as to provide the necessary technical input to support whatever decisions are needed. It should also be of sufficient quality to allow independent review and assessment by the regulatory body. Clearly, the level of detail will tend to increase as the programme progresses. However, in broad terms, it should always be sufficient to demonstrate that:

(a) The assessments (e.g. of transport safety, operational safety or post-closure safety) encompass all relevant scenarios (i.e. both design and non-design aspects).
(b) The chosen models (both conceptual and mathematical) are fit for purpose.
(c) The parameters used in the models are appropriate.

(d) Reasonable variability in the conceptual models and parameters has been taken into account.
(e) Overall, optimization has been achieved (paras 4.36–4.39).

III.18. The level of detail needed to demonstrate all of this will very much depend on the outcome of each assessment. Where an assessment (whether of transport safety, operational safety or post-closure safety) indicates that there is a large ‘margin of safety’ (i.e. that the calculated doses fall orders of magnitude below the regulatory constraint), demonstration of compliance may be straightforward and may be achieved with relatively few resources by showing that even quite conservative assumptions about the scenarios, models and parameters do not lead to non-compliance. However, where an assessment produces an outcome that is close to the regulatory constraint, conservative assumptions will sometimes lead to non-compliance, so here it may become necessary to justify discounting some of the more conservative scenarios and to establish with some precision what constitutes reasonable (and unreasonable) variability in the models and parameters. Such needs often entail quite far reaching investigations in terms of the development of conceptual models and the determination of uncertainties in parameters.

III.19 While these considerations apply equally to small scale and to larger scale disposal activities, other things being equal, the smaller, less hazardous inventory associated with borehole disposal should enable post-closure safety to be demonstrated more simply than for larger scale practices.

Justification, traceability and clarity

III.20. Crucial considerations in the documentation of any safety case are justification, traceability and clarity. These are especially important for confidence building, regardless of the stage reached in the development programme for a borehole disposal facility.

III.21. Justification means explaining the reasoning behind the various decisions taken, especially those that relate to safety. The justification should cover arguments both for and against the decision and should explain why one option was chosen over another.

III.22. Traceability means that an independent qualified person should be able to go back to the original sources of the various elements of the safety case and be able to understand how these elements have been put together to form the safety case.

III.23. Justification and traceability both require a well-documented record of (a) decisions and assumptions made in the development of the disposal facility and (b) the models and data used in arriving at a given set of results of the safety assessment. Good traceability is essential in enabling independent review.

III.24. Clarity requires a good structure and a presentation with sufficient explanation to allow not only the outcome of the safety assessments to be understood, but also the underlying reasons. This requires that the work should be presented in the documents in such a way that the intended audience can gain a good understanding of the safety arguments and their basis. Different styles and levels of document may be required to provide material that is useful to different audiences.

Appendix IV

SITE CHARACTERISTICS AND CHARACTERIZATION OF THE HYDROGEOLOGICAL PROPERTIES OF A SITE

IV.1. This appendix discusses characteristics relating to near surface and intermediate depth boreholes. It also outlines the main site characterization activities. In general, the selection of a site that combines favourable characteristics and avoids unfavourable ones will allow post-closure safety to be demonstrated more simply and with fewer resources than would otherwise be the case.

Boreholes with waste at a depth of less than 30 m below the surface

IV.2. With regard to the need to avoid the contamination of groundwater resources, a significant advantage of near surface boreholes is their potential capability to utilize permanently unsaturated host rocks. In some arid regions, there may be practically no near surface groundwater movement at all. In other circumstances, there may be some infiltration of meteoric water and percolation down to the water table. The absence of significant quantities of groundwater — a major medium for radionuclide transport — will delay the interactions between the radionuclides and the saturated zone, reducing the importance of the groundwater pathway and allowing time for radionuclides to decay in the unsaturated zone. All this is advantageous to post-closure safety and allows safety to be demonstrated more simply and with fewer resources.

IV.3. To provide reasonable confidence that the host rocks would remain unsaturated over the relevant containment period, it would be necessary to characterize the site so as to estimate possible future movements of the groundwater table or temporary saturation of the host rock. In this characterization, account should be taken of present and past hydrogeological conditions, future climatic conditions and possible rates of erosion. This is not to say that saturation must be entirely avoided, but sites where the rocks in the waste disposal zone would be saturated fairly frequently — seasonally or perhaps every few years — should generally be avoided. This is because cyclical wet and dry conditions or even a permanently partly saturated environment can produce severe corrosion conditions. The reason for this is that ephemeral groundwaters have oxidizing properties and may contain high concentrations of solutes. At some sites, the need to avoid saturated conditions may represent a special challenge: that of reconciling the need for placing the waste deep enough to provide adequate isolation with the need for keeping the waste above the water table. Borehole cores may preserve evidence of past groundwater levels.

IV.4. Where a near surface borehole is to be placed in a saturated environment, there should be a low groundwater flow. This is most likely to arise from low permeability rocks (e.g. clay), probably combined with low hydraulic gradients, and will result in a low flux of radionuclides out of the borehole. If this is combined with strong sorption (see para. IV.14) in the surrounding rocks, this will produce further retardation of radionuclides and allow a more simple demonstration of post-closure safety.

IV.5. Saturated near surface sites where there is very low groundwater flow may also have anoxic or chemically reducing conditions. This can benefit disposal by reducing corrosion and, perhaps, by reducing the solubility of a few polyvalent radionuclides such as technetium and plutonium. In many cases, it may be possible to induce limitations on solubility by providing a cementitious (and therefore alkaline) environment. Other aspects of the local geochemistry can have a negative effect on the engineered barriers. These include sulphate-bearing groundwaters, which may lead to the early degradation of concrete made from ordinary Portland cement. Also, high chloride levels can be detrimental to containers by causing corrosion.

IV.6. As a result of weathering, rock competence near the surface will usually be insufficient to allow a near surface borehole (especially one of large diameter) to be self-supporting. For this reason, borehole casing will often be required. This implies that formations in which it is practicable to place good, behind casing seals or grout-to-rock seals are to be preferred. Ground where the levels have been changed by moving or importing material should be avoided because of its generally lower stability.

IV.7. Sites should be examined for surface processes such as flooding, landslip, erosion and weathering. The incidence of flooding should be of particular concern because of its influence on erosion through valley deepening and also because of its capability to disrupt operation of the facility. For the same reason, the incidence of extreme meteorological events should also be considered in site selection. In general, the active part of the borehole disposal system should be located below the local erosion base and, in any event, the rate of erosion should be sufficiently low to avoid exposure of the waste over the assessment time frame (see para. 3.9).

IV.8. Near surface borehole disposal facilities will be more susceptible to inadvertent human intrusion than deeper boreholes and the resource and development potential of the site and its immediate surroundings should therefore be considered. Outright ownership of the site should be obtained and sites situated close to possible water or mineral resources should be avoided. The possibility of groundwater extraction, quarrying, tunnelling, mining and mineral exploration by drilling should be considered. To reduce the possibility of inadvertent intrusion due to construction activities, near surface sites that are close to areas of high population density or that are on the fringes of expanding urban areas should not be chosen.

IV.9. Environments where there is ongoing local tectonic activity should be avoided. Thus, sites that are close to active fault lines or areas prone to frequent seismic activity are unlikely to be suitable.

IV.10. Other factors that are likely to be influential in site selection for near surface borehole disposal facilities are:

(a) Geological and hydrological complexity, which will considerably complicate both site characterization and modelling and will increase the resources required for these tasks.
(b) Access, which should be good enough to allow heavy vehicles (e.g. excavators or truck mounted drilling rigs) to reach the site; for small scale disposals, mobile supplies of electricity and water should be adequate.

Boreholes with radioactive waste disposed of more than 30 m below the surface

IV.11. For intermediate depth boreholes, disposal can also be in the unsaturated zone and, exactly as explained above for boreholes at lesser depths, such sites are highly advantageous from the point of view of post-closure safety. More probably though, intermediate depth boreholes will be located in fully saturated conditions at greater depth. Here, the significance of the groundwater pathway for many radionuclides should be diminished by means of a low groundwater flux. A low groundwater flux arises from the presence of low permeability rocks, combined with low hydraulic gradients. For intermediate depth boreholes sunk to depths of a hundred metres or more, suitable host rock formations may contain old, possibly saline, groundwater indicative of very slow flow and little mixing with shallower waters over time periods that are equivalent to the containment periods of interest. Saturated conditions at greater depths will often provide anoxic or even reducing conditions, which, as explained above, are beneficial in reducing corrosion and, possibly, reducing the solubility of a few polyvalent radionuclides. As with near surface borehole disposal, sites where conditions alternate between saturated and unsaturated should be avoided.

IV.12. Important considerations for fully saturated sites are dilution by mixing and dispersion, which can be useful mechanisms for attenuating the impact of disposal, especially in the long term, when engineered barriers begin to fail and the migration of some radionuclides becomes inevitable. For dilution and dispersion to be effective, the prime necessity is radionuclide containment. Thus, in the case of dilution, a small flux of radionuclides (in becquerels per year) migrating into, and mixing with, a large volumetric flux of groundwater (in cubic metres per year) will produce a low concentration of radionuclides in the groundwater (in becquerels per cubic metre), which will result in low doses. Dispersion refers to the spreading out in time and space of a radionuclide plume migrating from a repository. By far the most important aspect is dispersion in time and, again, this is most effective in reducing calculated doses when the retention and retardation of radionuclides are at their greatest.

IV.13. Both dilution and dispersion are assisted by strong containment of radionuclides, which is determined by the effectiveness of the engineered barriers and, importantly in a site selection context, long radionuclide migration times to the surface. This will be produced by low groundwater flow (see para. IV.11) and strong radionuclide sorption (see para. IV.14) in the surrounding geosphere. High levels of dilution due to mixing may also be achieved where there is a strong contrast in groundwater flow between the disposal horizon with very low flow and the nearer surface horizons with higher flow.

IV.14. Strong sorption (for the radionuclides to be disposed of and their radiologically significant progeny) in the host rocks and overlying formations is another favourable factor that aids containment. At the same time, it has to be acknowledged that some non-sorbing ions (e.g. chloride) exhibit little sorption regardless of rock type. The term sorption is used to describe a range of processes, including adsorption, ion exchange and chemical reaction, that allow radionuclides to attach themselves to near field materials such as bentonite or cement or to rocks in the geosphere. This retards the transport of these radionuclides, giving more time for radioactive decay to occur. Sites where sorption causes radionuclide transport to be slow and where dilution by mixing and dispersion are high should give rise to calculated doses that fall well below the regulatory constraint. Where this is the case, the demonstration of post-closure safety may be possible with relatively less effort.

IV.15. It is advantageous to the construction of the borehole if the host rock is self-supporting and, for this reason, rock competence will be important. Rock and deep soil formations that have poor stability for boreholes should be avoided, particularly for the host unit. Where competent rock is combined with a small borehole diameter, it may be possible to dispense with a borehole casing in the disposal zone. However, close to the surface, because of lower rock competence (due to weathering), casing will often be required. Where borehole casing is to be installed in the disposal zone, a behind casing seal will need to be installed. Such seals are usually created by pumping cement grout into the annulus between the casing and the rock. Rock formations where good grout-to-rock bonding is possible are therefore to be preferred. Ground where the levels have been changed by exporting or importing material should be avoided because of its generally lower stability.

IV.16. For intermediate depth boreholes, the likelihood and the consequences of human intrusion will usually be less than for near surface boreholes. Nonetheless, disposal sites should be chosen to reduce the possibility of inadvertent human intrusion by avoiding areas with useful natural resources (e.g. plentiful groundwater, minerals or hydrocarbons). With respect to access, unpaved roads should be adequate for small scale disposals and it should be possible to use mobile supplies of electricity and water.

IV.17. Again, as with near surface boreholes, sites should be chosen to avoid areas of ongoing tectonic activity.

IV.18. Surface processes, while they are less important for an intermediate depth borehole site, should still be considered: it is likely, for instance, that erosion and weathering will be more tolerable for an intermediate depth borehole than for a near surface borehole. Areas susceptible to flooding and landslip should again be avoided, as much for reasons of operational safety as for post-closure safety.

IV.19. With respect to climate and extreme meteorological events, the principal concern for intermediate depth boreholes is their effect on regional groundwater flow. Disposal in formations where the groundwater shows strong seasonal variability should be avoided.

IV.20. Owing to the difficulty of characterizing deep formations by boreholes alone, a simple, easily characterized geological structure and hydrogeological system is advantageous. Areas of high geological complexity should be avoided because they could be difficult (and therefore expensive) to characterize and this could limit the degree of confidence in the results of the safety assessment.

Hydrogeological characterization activities

IV.21. To help describe the hydrogeological characterization of a site, it is useful to define three situations:

(1) A borehole situated in an unsaturated zone;
(2) A borehole situated in a saturated environment with high to low permeability rocks;
(3) A borehole situated in a saturated, very low permeability (e.g. clay) environment.

IV.22. The following three subsections briefly describe the characterization activities likely to be needed for hydrogeological characterization of each type of site. The discussion presupposes (a) that the disposal is on a small scale and (b) that the geology, hydrology and geochemistry of the site are not complex. In all three cases, an early and important component of the work will be to establish the geochemistry of the site at the proposed disposal depth. The purpose of this component is to provide assurance that the local geochemistry (e.g. sulphate and chloride levels) will not unduly affect the engineered barriers.

Hydrogeological characterization of an unsaturated site

IV.23. Even in temperate and wet tropical regions, the water table may sometimes lie 10–20 m below the surface: sufficiently deep to allow a near surface borehole to be located in the unsaturated zone. On the other hand, unsaturated zones that are sufficiently deep to accommodate an intermediate depth borehole are likely to be confined to arid regions.

IV.24. At a site where the water table is tens or even hundreds of metres below the disposal zone, the investigatory borehole should normally extend to the water table and, for near surface boreholes, to the aquitard that supports it. Provided that the regional hydrogeology is generally understood, one investigatory borehole may be sufficient for a small scale disposal facility. This borehole should provide core from the host formation (at least) and water samples from the underlying aquifer. Key information to be established includes evidence for previous levels reached by the water table, the amount and rate of percolation of meteoric water through the unsaturated zone, and the characteristics of the groundwater in the underlying aquifer. These characteristics include details of its chemistry, origin, age, flow and pressure, which are used to estimate its transit time to the biosphere. Where the testing fails to provide confidence in the regional hydrogeological model, additional boreholes may be necessary to help develop one.

Hydrogeological characterization of a saturated site in high to low permeability rocks

IV.25. The second example is a borehole disposal facility situated in high to low permeability rocks that are permanently saturated. Here, to confirm that there are no structures or hydrogeological features such as underlying high pressure zones that could affect performance, the investigatory borehole should be sunk at least to the bottom of the host formation (unless this is very deep). Hydrogeological investigations should include measurements of pressure and water inflow rate at different horizons and pump testing to establish the effective hydraulic conductivity of the host rocks. Additional investigatory boreholes, distributed in the surrounding area, are also likely to be needed. These should be used to establish the pressure gradient and the degree of homogeneity of the host rocks. These secondary boreholes should normally be drilled at least to the disposal depth. In the case of near surface boreholes situated in or close to the saturated zone, the secondary boreholes should also be used to determine the morphology of the water table and how it varies seasonally. Extracted core may provide evidence of past water table levels. For the intermediate depth borehole disposal facilities, water samples taken from different depths should be used to assess the degree of stratification of the water column.

Hydrogeological characterization of a saturated site in very low permeability rocks

IV.26. At sites where the disposal zone is situated in saturated, very low permeability rocks (e.g. plastic clay), the rate of water ingress into investigatory boreholes may be very low or even undetectable, and this may make the collection of water samples and the measurement of hydrogeological properties difficult. In some cases, it may be possible to extract water samples from extracted core and it may be necessary to assign a figure to the groundwater flow rate on the basis of the limit of detectability of water ingress to the borehole. The hydraulic conductivity of the host rock can be measured from extracted core. The thickness of the host rock layer should be measured to establish the distance between the disposal zone and more permeable rocks.

Provided that the host rock is relatively homogeneous, a single investigatory borehole may be sufficient for a small scale disposal facility. Otherwise, it may be necessary to sink shallow boreholes or use other techniques to locate, for instance, lenses or layers of higher permeability material.

Appendix V

A POSSIBLE SURVEILLANCE AND MONITORING PROGRAMME SUITABLE FOR A SMALL SCALE BOREHOLE DISPOSAL FACILITY

V.1. The surveillance and monitoring activities described here are not intended to be prescriptive — the operator of a disposal facility should justify the extent of the proposed programme. However, for a borehole disposal facility consisting of fewer than twenty boreholes for disused sealed sources, the following suggestions may be adequate.

Pre-operational (baseline) surveillance and monitoring

V.2. Baseline measurements should be made well before the site becomes operational (e.g. during the site characterization phase). The purpose of baseline surveys is to build up a reliable and comprehensive database of information relating to the site so that any future changes can be readily detected. These could cover a period of at least one year (i.e. covering all the seasons) and should consist of meteorological data gathered daily and continuous seismic data, together with:

(a) Surface samples: monthly measurements of activity levels in air, soil (including radon if it is anticipated that the sources will contain radium) and surface water (if any), with identification of the principal radionuclides.
(b) Borehole groundwater samples: monthly measurements of activity levels in groundwater in the disposal horizon, if this is water bearing, or otherwise just below the groundwater table, provided that this is no more than 100 m below the disposal horizon. Again, the principal radionuclides should be identified.

V.3. Surface sampling should be done at about ten locations within and around the boundary of the proposed site. About half of these locations would be used repeatedly; the other locations would be changed each month so that, over the full year, sampling points are uniformly distributed over the area to be covered. Other surface sample points would be located at the nearest human habitation and the point of putative groundwater discharge (e.g. a nearby topographic low). If borehole water is used at locations nearby, this should also be monitored.

V.4. For borehole groundwater sampling, two to four boreholes should be located on the site boundary to sample water in the disposal horizon upstream and downstream of the waste. Once a reliable database has been established, the frequency of sampling could be reduced to twice yearly.

Surveillance and monitoring during the operational period

V.5. When the operational period begins, the amount of on-site surveillance and monitoring should be increased. For instance, the measurements should include monitoring of personnel, monitoring of newly received waste packages for radioactive contamination and monitoring for the spread of contamination from packages to handling equipment. When waste handling is in progress, air monitoring for particulates should be continuous, with filters being removed for analysis after every major site operation. Following waste emplacement, soil samples should be used to monitor contamination (if any) of the soil around the borehole.

V.6. Beyond the site boundary, sampling and analysis of air, soil and water should continue at the same twice yearly frequency as previously — provided, of course, that the results continue to be satisfactory. Meteorological and seismic measurements should also be continued.

Surveillance during the post-closure period of institutional control

V.7. Following closure of the facility, surface sampling of air, soil and water should continue at the same frequency as during the operational period. Again, about ten surface sample locations should be sufficient, with additional samples taken at the nearest human habitation, a topographic low and any nearby boreholes used for water extraction.

V.8. For groundwater sampling, two monitoring boreholes should be sufficient, one upstream of the waste, the other downstream. If the institutional period is to exceed five years, the number of surface samples could be halved, the upstream borehole could be sealed and the sampling frequency could be reduced to once a year. The final monitoring borehole would be sealed when the period of institutional control ends.

Appendix VI

MANAGEMENT SYSTEMS

Setting up a management system

VI.1. The first requirement for the establishment of a management system is the formal endorsement of such a system at the highest level of management of an organization and a commitment to ensuring that it is fully implemented throughout the organization [35]. A management system is a means of ensuring that an organization's goals are achieved efficiently and effectively. It follows that the organization's goals should be a focal point of the management system. If, for example, in establishing the remit of an operator of a borehole disposal facility, a government were to stress the importance of cost efficiency, this should appear as one of the operator's goals.

VI.2. With the organization's goals clearly stated, a management system should be developed and implemented to achieve these. This is often done by breaking down the goals in a hierarchical way — into 'activities' and 'tasks' for instance — and structuring the organization to reflect this breakdown. This means that the organizational structure and job descriptions form part of the management system. How the goals–activities–tasks are to be performed and by whom is documented in policies, procedures, work instructions, quality plans, etc. In Ref. [35], all of these are called 'working documents' and this convention will be followed here. The management system should apply to all the work of an organization, i.e. from conceptual design through to the ending of institutional control. The management system should also extend to suppliers and contractors, who should also be expected to work to agreed procedures. In this context, nationally and internationally recognized codes, regulations and standards provide practical, widely understood benchmarks and should be followed whenever possible.

VI.3. In the case of an operator, the management system should extend to the waste producers who might have their waste packaging arrangements audited by the operator. In turn, the operator's management system should be approved by the regulatory body.

Working documents

VI.4. Working documents should describe what work is to be performed, how and by whom so as to complete it successfully (i.e. in such a way that the work contributes to the achievement of the organization's goals). The working document should also require the production of documentary evidence to prove that the working document was followed. Working documents should be written by someone with experience in carrying out the task and should be independently approved, preferably by someone at the senior management level.

VI.5. The level of detail and prescription in a working document should depend on how important the work is for safety and its susceptibility to failure. In general, the safety case and, more particularly, the safety assessments within it should be used to help identify and justify the level of detail and prescription needed in individual procedures. The safety case should also provide a methodology for identifying information that should be preserved either as an audit trail for past decision making or because it could be important for future safety assessments.

VI.6. For example, in early design work, it is invention, not prescription, that is needed and, although the final design will be strongly safety related, a great deal of checking and testing will take place before the early design ideas become finalized. Consequently, the working document should focus on providing a clear description of the aim and the constraints of the design, together with a requirement to explain the reasoning behind the various design decisions. On the other hand, backfilling of a borehole should be tightly prescribed because (i) post-closure safety may depend on it, (ii) it may be difficult to check that it has been done correctly and (iii) a badly backfilled borehole could be very difficult to remedy. The accompanying documentation should aim to provide evidence that backfilling was (or was not) completed successfully. It could, for instance, state the volume of backfill placed in the borehole and the measured change in level in the borehole. For a third example, the ISAM approach [28] described in Appendix III provides an illustration of a well thought out working document for performing a post-closure safety assessment. Particularly useful is the initial 'context' step, which allows the supporting documentation to become more or less voluminous, depending on how the safety assessment is to be used.

Documentation

VI.7. A key function of the management system is the production and retention of documentary evidence to demonstrate that the correct procedures have been followed. Regular audits, which should also be documented, should provide additional evidence of this. Audits should be carried out by the organization itself (internal audits) and by external agencies. Where the organization is an operator, the actions and procedures to be followed by the operator in the event of the discovery of a non-compliance with safety procedures should be specified and approved by the regulatory body.

VI.8. By ensuring that compliance with the relevant safety requirements and criteria forms part of the operator's goals, activities and tasks, a management system will contribute to delivering compliance and, through the associated documentation, will provide evidence for this.

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Annex

GENERIC POST-CLOSURE SAFETY ASSESSMENT FOR BOREHOLE DISPOSAL OF DISUSED SEALED SOURCES

A–1. This annex is based on a report on a generic post-closure radiological safety assessment (GSA) for the borehole disposal concept, with the purpose of identifying the concept's key safety features, under varying disposal system conditions, in order to support the concept design and licensing processes and facilitate its site specific implementation. The report is one of a series that is being developed to support the implementation of the borehole disposal concept. The report is to be issued by the IAEA as a Safety Report.

A–2. Many countries now have radioactive sources that need to be managed and disposed of carefully and in a safe and secure manner. These sources contain different radionuclides in highly variable quantities. Many sources are small in physical size. However, they can contain very high activities, with typical levels in the megabecquerel (10^6 Bq) to petabecquerel (10^{15} Bq) range. Therefore, if they are not managed properly, radioactive sources can represent a significant hazard to human health and to the environment. Storage in a secure facility can be considered as an adequate final management option for sources containing quantities of short lived radionuclides, which decay to harmless levels within a few years. However, for most other sources, a suitable disposal option is required.

A–3. Many countries have existing or proposed near surface radioactive waste disposal facilities for low and intermediate level wastes. However, the specific activity of many sources exceeds the waste acceptance criteria for such facilities, since the source constitutes a high, localized concentration in the facility. Deep geological disposal offers the highest level of isolation available within disposal concepts currently being 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 expensive to develop and only viable for countries with extensive nuclear power programmes. Therefore, increasing attention has been given to the disposal of disused sources in borehole disposal facilities with a view to providing a safe and cost effective disposal option for limited amounts of radioactive waste and, particularly, disused sources.

A–4. A variety of borehole designs have been used for the disposal of radioactive waste at differing depths (a few metres to several hundred metres) and diameters (a few tens of centimetres to several metres). The design evaluated in this report is based on the narrow diameter (0.26 m) design developed under the IAEA's AFRA project (see Figs 1 and A–1) since this design has been developed specifically for the disposal of disused radioactive sources and uses borehole drilling technology that is readily available in all countries. The design can accommodate disused sources of less than 110 mm in length and 15 mm in diameter. This means that the design is applicable to a wide range of sources. It is assumed that the sources are disposed of at least 30 m below the ground surface. The geological, hydrogeological and geochemical conditions considered in this report have been selected to represent a broad spectrum of site conditions.

A–5. The GSA has been undertaken using an approach that is consistent with best international practice. Specifically, the approach developed by the Coordinated Research Project of the IAEA on Improving Long Term Safety Assessment Methodologies for Near Surface Radioactive Waste Disposal Facilities (the ISAM approach) has been used, with the aim of ensuring that the assessment is undertaken and documented in a consistent, logical and transparent manner. The ISAM approach consists of the following key steps:

(a) Specification of the assessment context;
(b) Description of the disposal system;
(c) Development and justification of scenarios;
(d) Formulation and implementation of models;
(e) Presentation and analysis of results.

Each of these steps is applied to the GSA of the borehole disposal concept and the application is described in this report.

A–6. The main report is supported by a series of appendices that provide detailed information relating to specific aspects of the assessment study, namely:

(a) The selection of the radionuclides and the geochemical conditions assessed in the GSA;

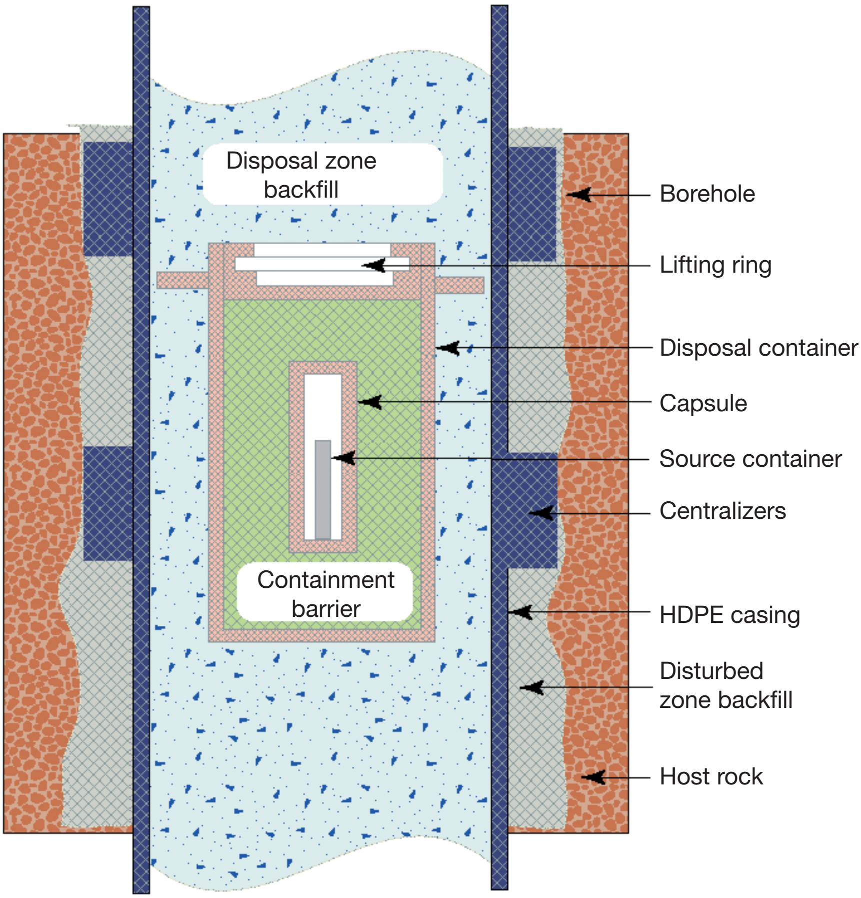

FIG. A–1. Illustrative section through a borehole used for disposal.

(b) The approach used to identify scenarios and conceptual models for consideration in the GSA and the screening of associated features, events and processes (in particular those associated with the borehole itself);
(c) The detailed models used to undertake the calculations of cement degradation and the corrosion of stainless steel waste capsules and disposal containers in the different environmental conditions considered;
(d) The assessment level models and data used to calculate the impacts of disposals to the borehole disposal concept;
(e) The results of the associated calculations.

A–7. The GSA has been developed so that it can serve as the primary post-closure safety assessment for specific disposal sites that lie within the envelope of conditions assessed in this report. For situations falling outside the envelope, additional calculations ranging from minor variations of the GSA to a full, site specific safety assessment may be required. In such cases, the GSA could be used to guide and support the development of the site specific assessment. Furthermore, the derived generic reference activity values could be used as a benchmark against which to compare values derived from the site specific assessment.

A–8. The results show that with a suitable combination of inventory, near field design and geological environment, the borehole disposal concept is capable of providing a safe solution for the disposal of both long lived and short lived radionuclides. For most radionuclides, including longer lived radionuclides such as ^{226}Ra, post-closure safety does not place unduly restrictive limitation on the radionuclide inventory that could be disposed of using the borehole disposal concept. Even for radionuclides such as ^{238}Pu, ^{239}Pu and ^{241}Am with exceedingly long lived progeny (i.e. half-lives in excess of 100 000 a), the concept has the potential to dispose of around 1 TBq in a single borehole.

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