IAEA SAFETY STANDARDS SERIES

Management of Radioactive Waste from the Mining and Milling of Ores

SAFETY GUIDE

No. WS-G-1.2

INTERNATIONAL
ATOMIC ENERGY AGENCY
VIENNA

IAEA SAFETY RELATED PUBLICATIONS

IAEA SAFETY STANDARDS

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www.iaea.org/ns/coordinet

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MANAGEMENT OF RADIOACTIVE WASTE FROM THE MINING AND MILLING OF ORES

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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''.

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FOREWORD

by Mohamed ElBaradei
Director General

One of the statutory functions of the IAEA is to establish or adopt standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes, and to provide for the application of these standards to its own operations as well as to assisted operations and, at the request of the parties, to operations under any bilateral or multilateral arrangement, or, at the request of a State, to any of that State's activities in the field of nuclear energy.

The following bodies oversee the development of safety standards: the Commission on Safety Standards (CSS); the Nuclear Safety Standards Committee (NUSSC); the Radiation Safety Standards Committee (RASSC); the Transport Safety Standards Committee (TRANSSC); and the Waste Safety Standards Committee (WASSC). Member States are widely represented on these committees.

In order to ensure the broadest international consensus, safety standards are also submitted to all Member States for comment before approval by the IAEA Board of Governors (for Safety Fundamentals and Safety Requirements) or, on behalf of the Director General, by the Publications Committee (for Safety Guides).

The IAEA's safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities. The standards are binding on the IAEA in relation to its own operations and on States in relation to operations assisted by the IAEA. Any State wishing to enter into an agreement with the IAEA for its assistance in connection with site evaluation for or the design, construction, commissioning, operation or decommissioning of a nuclear facility or any other activities will be required to follow those parts of the safety standards that pertain to the activities to be covered by the agreement. However, it should be recalled that the final decisions and legal responsibilities in any licensing procedures rest with the States.

Although the safety standards establish an essential basis for safety, the incorporation of more detailed requirements, in accordance with national practice, may also be necessary. Moreover, there will generally be special aspects that need to be assessed on a case by case basis.

The physical protection of fissile and radioactive materials and of nuclear power plants as a whole is mentioned where appropriate but is not treated in detail; obligations of States in this respect should be addressed on the basis of the relevant instruments and publications developed under the auspices of the IAEA. Non-radiological aspects of industrial safety and environmental protection are also not explicitly considered; it is recognized that States should fulfil their international undertakings and obligations in relation to these.

The requirements and recommendations set forth in the IAEA safety standards might not be fully satisfied by some facilities built to earlier standards. Decisions on the way in which the safety standards are applied to such facilities will be taken by individual States.

The attention of States is drawn to the fact that the safety standards of the IAEA, while not legally binding, are developed with the aim of ensuring that the peaceful uses of nuclear energy and of radioactive materials are undertaken in a manner that enables States to meet their obligations under generally accepted principles of international law and rules such as those relating to environmental protection. According to one such general principle, the territory of a State must not be used in such a way as to cause damage in another State. States thus have an obligation of diligence and standard of care.

Civil nuclear activities conducted within the jurisdiction of States are, as any other activities, subject to obligations to which States may subscribe under international conventions, in addition to generally accepted principles of international law. States are expected to adopt within their national legal systems such legislation (including regulations) and other standards and measures as may be necessary to fulfil all of their international obligations effectively.

EDITORIAL NOTE

An appendix, when included, is considered to form an integral part of the standard and to have the same status as the main text. Annexes, footnotes and bibliographies, if included, are used to provide additional information or practical examples that might be helpful to the user.

The safety standards use the form 'shall' in making statements about requirements, responsibilities and obligations. Use of the form 'should' denotes recommendations of a desired option.

The English version of the text is the authoritative version.

CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. The radioactive waste generated in mining and milling activities, especially those involving uranium and thorium (U, Th) ores, differs from that generated at nuclear power plants and most other industrial operations and medical facilities. Waste from mining and milling activities contains only low concentrations of radioactive material but it is generated in large volumes in comparison with waste from other facilities. The management methods to be employed are therefore different and will usually involve waste disposition on or near the surface, in the vicinity of the mine and/or mill sites. Furthermore, the waste will contain long lived radionuclides, and this has important implications for its management because of the long time periods for which control will be necessary.

1.2. Radioactive waste arises from all stages of mining and milling processes and includes, in addition to mill tailings, waste rock[1], mineralized waste rock[2] and process water, including leaching solutions. Rainfall and snowmelt runoff and seepage from stockpiles and areas of uranium process plants should also be managed.

1.3. The hazards to humans or to the environment posed by mining and milling waste arise not only from its radioactivity but also from the presence of toxic chemicals and other materials in the waste. Achieving a consistent regulatory approach to protect against these different hazards is a challenge for national regulators. This publication is focused on the management of the radiological hazards associated with the waste, but where there is a particular need for regulators to take account of the non-radiological hazards, this is also indicated.

1.4. This publication supersedes Safe Management of Wastes from the Mining and Milling of Uranium and Thorium Ores, Safety Series No. 85, issued in 1987.

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[1] Waste rock is material that is excavated from a mine and which does not present any significant radiological hazard requiring management to protect human health or the environment. Waste rock may still require management for other reasons, such as to control erosion to prevent the siltation of local surface water bodies.

[2] Mineralized waste rock is material that is excavated from a mine and which has chemical and/or radiological characteristics which necessitate its management to protect human health or the environment.

OBJECTIVE

1.5. The objective of this Safety Guide is to provide recommendations and guidance on the safe management of radioactive waste that results from the mining and milling of ores. The recommendations of this Safety Guide apply primarily to new facilities. Existing facilities may not necessarily be in compliance with all of these recommendations. However, in accordance with national policies, appropriate steps may be taken to review the safety of existing facilities and, where reasonably practicable, to upgrade their safety in line with the relevant recommendations set out in this Safety Guide.

SCOPE

1.6. This Safety Guide addresses strategies and protocols for the siting, design, construction, operation and closure of facilities that are necessary to protect workers, the public and the environment from the impacts, both now and in the future, of radioactive waste arising from the mining and milling of ores. Closure means the technical and administrative actions required to place a waste management or disposal facility in an acceptable condition at the end of its operating life. Closure may apply to mill tailings: piles of mining debris and heap leach piles. Other parts of facilities used for the mining and milling of U/Th ores (for example, surface structures) can be decommissioned by adopting the approach taken in other parts of the nuclear industry. Recommendations and guidance for such decommissioning are provided in another IAEA publication [1].

1.7. This Safety Guide provides recommendations on those waste management activities associated with the mining and milling of ores that are deemed to be practices.[3] Owing to poor waste management practices employed in the past, the mining and milling of some ores have frequently resulted in the generation of waste for which the application of all the principles developed for practices is inappropriate.

[3] A practice, as defined in the Basic Safety Standards (BSS), is "Any human activity that introduces additional sources of exposure or exposure pathways or extends exposure to additional people or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure of people or the number of people exposed" [2]. It should be noted that in some regional organizations the term practice does not cover activities in which naturally occurring radioactive material is involved, where this material is not used for its radioactive or fissile properties. This material may therefore be subject to different provisions of the regulations.

In such cases, the regulatory body should decide whether to treat waste management activities for these situations as practices or as interventions.[4]

1.8. The guidance contained in this publication is particularly applicable to the mining and milling of U/Th ores. However, it may also be applicable to the management of waste arising from the mining and milling of other ores having elevated activity concentrations (for example, mineral sands, metals and phosphate rock). This waste requires management because the radionuclides it contains could cause harm to humans and to the environment. In these cases, regulatory bodies should determine the relevance of the guidance on the basis of the requirements for protection and safety established in the BSS and in national regulations.

1.9. This Safety Guide does not address the use of facilities intended for the management of mining and milling waste for the disposal of radioactive and non-radioactive hazardous waste arising from other parts of the nuclear fuel cycle or from other practices. The chemical, physical and radiological nature of such waste may be substantially different from that of mining and milling waste; for example, materials contaminated with fission or activation products may need different engineering for handling and disposal. Consequently, other safety and environmental aspects, in addition to those dealt with in this Safety Guide, should be taken into account in considering the co-management of other waste [3, 4].

1.10. Radiological safety in the production and processing of U/Th ores is addressed in other IAEA publications [5, 6].[5] The control of occupational and public exposures and environmental impacts due to routine radioactive releases or transport of waste are also discussed in other IAEA safety standards [7, 8].

1.11. Certain non-radiological characteristics of the waste may pose significant hazards and risks which need to be addressed. Detailed consideration of the requirements to protect human health and the environment against these hazards and risks is outside the scope of this Safety Guide. However, such hazards should be considered in the comprehensive optimization of protection, which this Safety Guide covers.

[4] An intervention, as defined in the BSS, is "Any action intended to reduce or avert exposure or the likelihood of exposure to sources which are not part of a controlled practice or which are out of control as a consequence of an accident" [2].

[5] A Safety Guide on occupational radiation protection in the mining and processing of raw materials is in preparation.

STRUCTURE

1.12. The administrative, legal and regulatory framework needed for the safe management of waste resulting from mining and milling is described in Section 2. Principles and criteria used for defining an acceptable level of safety during the operation and after the closure of waste management facilities are discussed in Section 3. The extent to which human health and the environment are protected from waste arising from the mining and milling of ores will depend on the characteristics of the waste, the site and the waste management facilities. Strategies for managing waste are discussed in Section 4. Safety considerations for waste management in all phases of mining and milling activities are discussed in Section 5. A process for considering all the relevant issues associated with developing a waste management strategy and waste management facilities to ensure that human health and the environment are afforded an acceptable level of protection ('safety assessment') is discussed in Section 6. Guidance on the design and implementation of a quality assurance programme for waste management is provided in Section 7. A monitoring and surveillance programme for waste management facilities is discussed in Section 8. Institutional control of waste management facilities after closure is discussed in Section 9.

2. ADMINISTRATIVE, LEGAL AND REGULATORY FRAMEWORK

NATIONAL POLICY AND STRATEGY

2.1. States planning to engage in mining and milling activities are required to develop:

(a) A national policy for managing the associated waste;
(b) A strategy for implementing this policy, including the provision of necessary resources (Ref. [3], Principle 6).

2.2. The policy and strategy should reflect, and be consistent with, the principles for radioactive waste management as set out in Ref. [3] and Sections 3–6 of this publication.

2.3. Most U/Th mining and milling waste contains non-radiological hazardous components similar to those present in waste from other mining activities. States, in developing a national policy and strategy, should seek to deal in a consistent manner with all hazardous components arising during the mining and milling.

2.4. States should consider the need for, and the extent of, public involvement and consultation during the regulatory process. Increasing public consultation is a feature of the authorization process in many States. However, the responsibility for the regulatory decision remains with the regulatory body. The decision making process should be transparent, independent and defensible, such that if a decision is challenged the regulatory body can explain how it was reached.

2.5. The regulatory body should maintain a high level of understanding of the technical issues facing, and the financial circumstances of, the operator so as to ensure that the facility is operated safely and that sufficient funding has been allocated to allow for response to any accidents and closure operations.

RESPONSIBILITIES

2.6. The requirements for overall responsibilities in the management of radioactive waste are set out in detail in Ref. [9]. This includes the establishment of a legal framework and an appropriate regulatory body.

Regulatory body

2.7. The regulatory body is responsible for developing appropriate rules, criteria and guidelines, and for establishing a suitable licensing system within the legal framework. This implementation process should provide for general requirements and activities (e.g. rule making and setting licensing criteria) and specific requirements (e.g. requirements for inspections and radiological safety reviews), and should clearly define the responsibilities of the parties involved. It should also address the entire mining and milling life-cycle in relation to issues pertinent to the management of waste. An example of the regulatory process for a new mining and milling facility is provided in Fig. 1, from which the regulatory process in individual States may differ in detail. The regulatory body should ensure that all legal requirements have been fulfilled by the operator.

2.8. After closure of a mining and milling facility and assurance that the operator has fulfilled its obligations, the regulatory body should ensure that responsibility for the waste is transferred from the operator to an appropriate body with the powers to implement any required institutional control [4]. In many cases, the body having the greatest potential for maintaining these controls is a governmental organization. The regulatory framework should provide a mechanism for this transfer of responsibility. A mechanism should also be provided to ensure that the funding necessary to support institutional control is, and continues to be, available. These mechanisms or plans for their establishment should be identified early in the development of the operations.

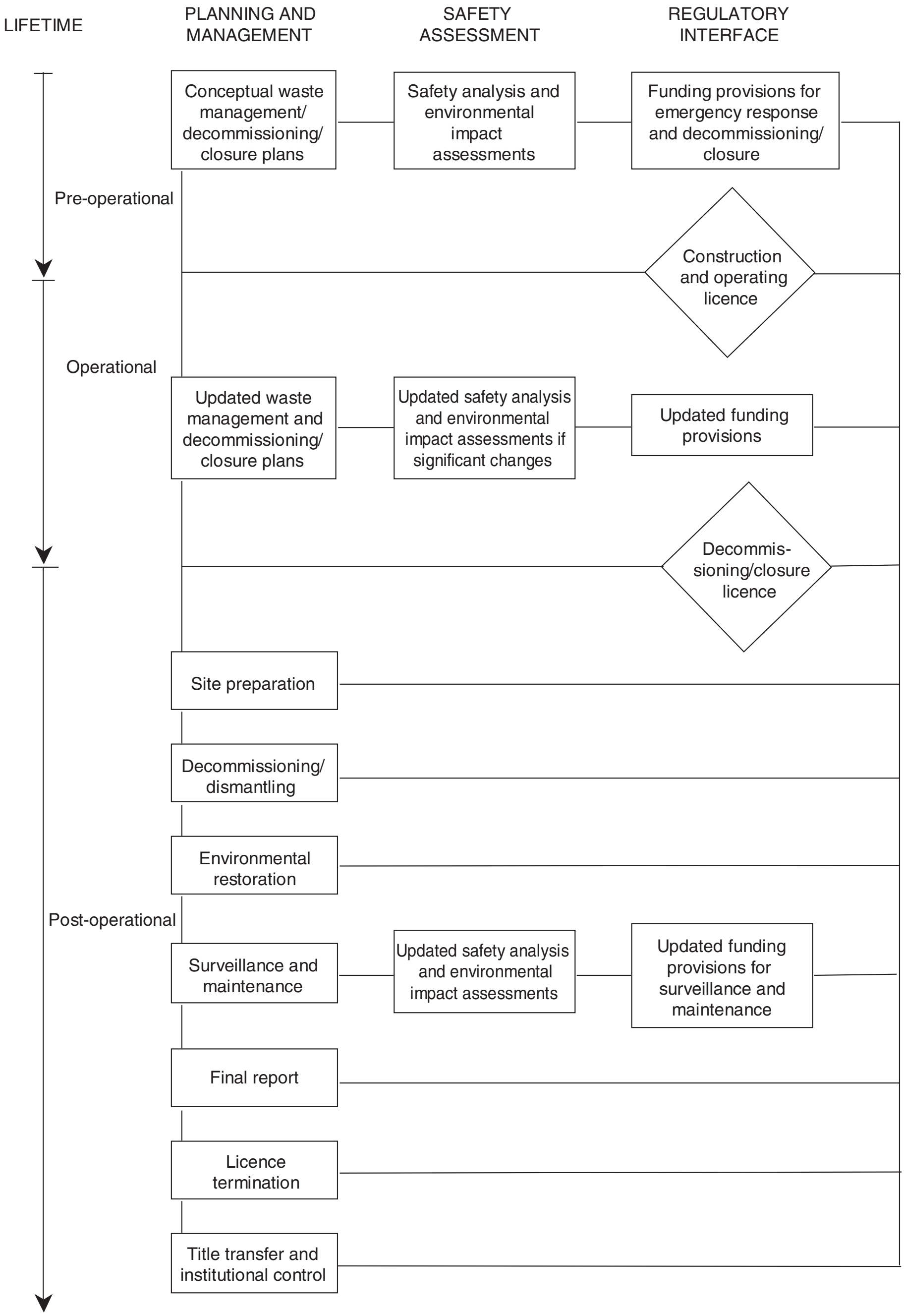

FIG. 1. Example of the regulatory process to be used in new facilities for managing waste from mining and milling.

2.9. The regulatory body should ensure that a mechanism is established to advise prospective purchasers of land affected by waste from the mining and milling of ores of all relevant details including:

(a) The nature of the waste and the extent to which the land is affected;
(b) Any restrictions on the use of the land;
(c) Any obligations of the landowner with respect to monitoring, surveillance and maintenance.

2.10. It should also be ensured by means of this mechanism that the appropriate body is informed of any impending transfer of ownership of the land so that this body can ensure that the vendor has fully discharged its responsibility with regard to informing the prospective purchaser of relevant details as stated in para. 2.9.

Operator

2.11. The operator of facilities for managing mining and milling waste is required to be responsible for all aspects of safety of the facility, including the protection of workers, the public and the environment from any hazards associated with the waste, up to and including the completion of closure of the facilities (Ref. [10], para. 3.11). The operator is also required to be responsible for complying with all legal requirements. If, for any reason, the operator can no longer assume this responsibility, it should be assumed by a governmental organization.

2.12. The operator of mining and milling facilities should develop technical and administrative proposals, taking into account quality assurance requirements (Ref. [10], para. 7.6), for all aspects of the protection of human health and the environment, which should be adopted subject to review and approval by the regulatory body.

3. PROTECTION OF HUMAN HEALTH AND THE ENVIRONMENT

GENERAL

3.1. The management of mining and milling waste is required to include the implementation of measures that will provide acceptable protection of human health and the environment, in comptiance with the requirements and recommendations of the IAEA, stated in Refs [2, 5, 6], and the International Commission on Radiological Protection (ICRP) [11–13].

3.2. The management of mining and milling waste is part of the management of a practice as defined in the BSS and radiation protection considerations are therefore governed by the principles of justification, optimization and dose limitation. The generation and management of this radioactive waste do not need to be justified since this will have been taken into account in the justification of the entire mining practice.

3.3. It has generally been accepted that the application of measures for the radiological protection of human health, in compliance with the requirements of the BSS, is sufficient to ensure that other species are not put at undue risk. Regulatory bodies should develop criteria for their particular situations where this may not be the case.

3.4. Figure 2 outlines the process described in this Safety Guide which should be followed to ensure an acceptable level of protection of human health and the environment from exposure due to mining and milling waste. It should be recognized that many of the steps identified in Fig. 2 are interdependent.

RADIOLOGICAL PROTECTION OF WORKERS

3.5. Workers at mines or mills may receive radiation doses from ores, concentrates, the product of the milling process (for example, U_3O_8), associated airborne dust, process fluids, industrial and analytical sources (for example, gauges and analytical equipment using X ray fluorescence), radon and thoron daughter products, and radioactive waste. The protection of workers from the radiological hazards of mining and milling waste should not be considered in isolation without considering these other sources of radiation exposure. The operators of the mine and mill should have in place a comprehensive radiological protection programme, in compliance with the requirements of the BSS, which addresses all sources of occupational radiation exposure associated with the mine and mill, including radioactive waste.

3.6. It is required that the dose due to occupational exposure of workers at mines or mills, all sources of exposure including radioactive waste being considered, not exceed: an effective dose of 20 mSv per year averaged over five consecutive years; an effective dose of 50 mSv in any one year; an equivalent dose to the lens of the eye of 150 mSv in a year; and an equivalent dose to the extremities (hands and feet) or the skin of 500 mSv in a year (Ref. [2], para. II-5).

3.7. It is also required that radiological protection be optimized so that doses to the workforce are as low as reasonably achievable (ALARA), social and economic factors being taken into account (Ref. [2], para. 2.24).

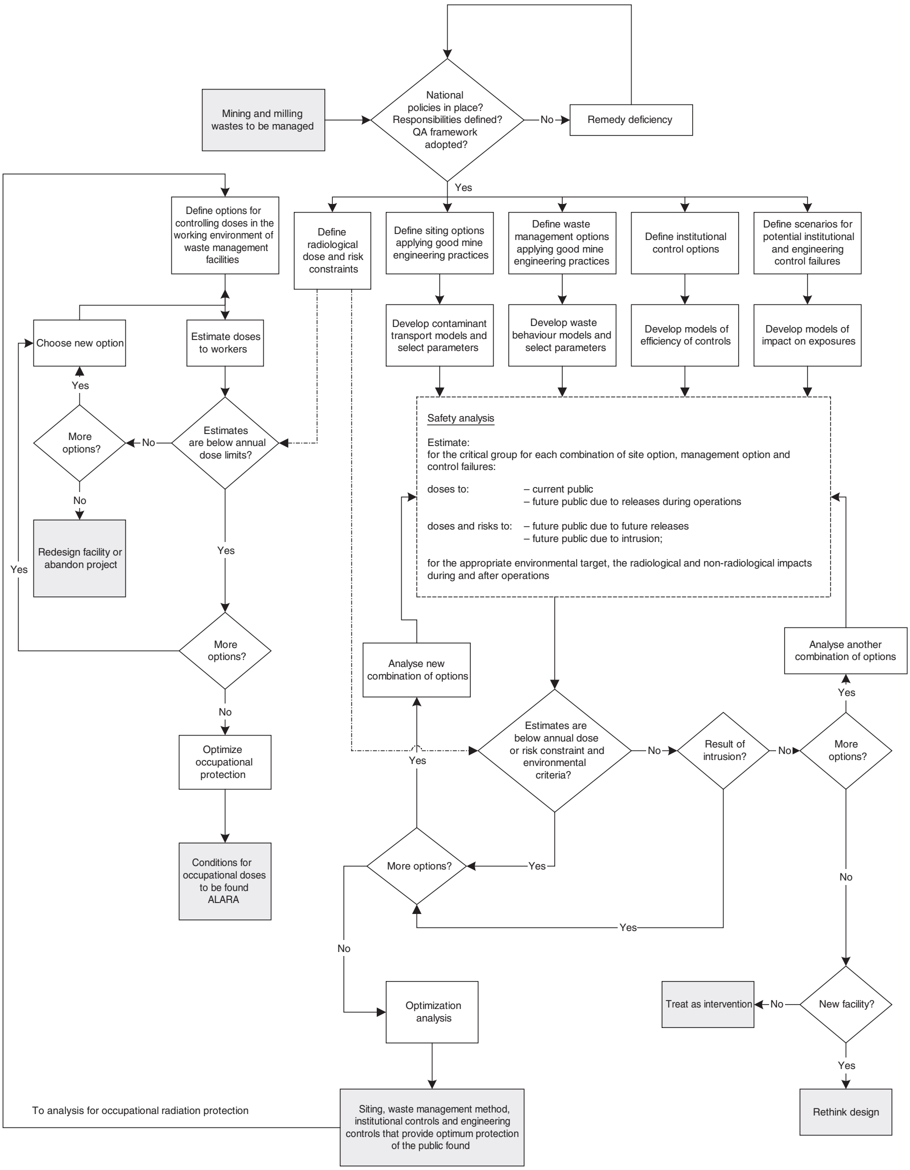

FIG. 2. Process for managing mining and milling waste.

3.8. Radioactive waste from mines and mills is an unsealed source. Hence, the following exposure pathways should be taken into account for the protection of workers:

(a) External gamma and beta irradiation, including skin contamination;
(b) Inhalation of aerosols, dust and gases;
(c) Ingestion.

3.9. The occupational radiation protection programme should be consistent with the recommendations and guidance provided in Refs [14–16].

RADIOLOGICAL PROTECTION OF THE PUBLIC

3.10. Releases of radionuclides from radioactive waste to the environment during mining and milling activities and subsequent waste management activities may result in the radiation exposure of members of the public. Such releases are subject to the criteria that are applicable to releases from any practice in which radioactive material is being handled and, as with occupational protection, national requirements for radiological protection should be consistent with the BSS [2]. However, since mine and mill tailings will continue to present a potential hazard to human health after closure, additional analyses and measures may be needed to provide for the protection of future generations. Such measures should not be left until closure but should be considered and implemented throughout the design, construction and operation of the mining and milling facilities. The protection of the public, from the beginning of operations to post-closure, should be considered in its entirety from the beginning of the design of the facilities. The overall objective and subsidiary criteria developed explicitly for the management of radioactive waste should be consistent with these considerations.

3.11. Although mining and milling waste contains only naturally occurring radionuclides, these radionuclides cannot be considered to be in their original states or concentrations, since their physical and chemical forms may have been altered substantially, and exposures may be influenced by the operation of the waste management facilities. Exposures attributable to such waste should not be regarded as exposure to natural background radiation and exposures of the public attributable to all mining and milling waste should be included in the system of radiation protection for practices as required in the BSS [2].

Radiological protection in operations

3.12. Waste management facilities are required to be designed and operated so that in their operation the radiological protection of workers, the public and the environment is optimized, with doses kept ALARA, social and economic factors being taken into account (Ref. [2], para. 2.24). In addition, doses to the critical group of members of the public that are attributed to practices are required not to exceed an effective dose of 1 mSv in a year; or, under special circumstances, an effective dose of up to 5 mSv in a single year provided that the average dose over five consecutive years does not exceed 1 mSv per year (Ref. [2], para. II-8).

3.13. The dose limit established in Ref. [2] applies to all doses received by members of the critical group from all practices under regulatory control, including practices already current, whether or not relating to mining and milling. Regulatory bodies should therefore allocate an annual dose constraint for each mining and milling operation that will ensure that the overall dose limit will not be exceeded, with account taken of the releases and exposures expected from all other relevant sources and practices, including any known future facility or practice that may result in additional doses.

3.14. Radiation doses will be received by members of the public after closure owing to releases of radionuclides that occurred during operations. These doses should not exceed the annual dose constraint set by the regulatory body, such that the annual dose limit for members of the public will not be exceeded, with account taken of anticipated doses due to all relevant sources of exposure. This is following the principle that "Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today" (Ref. [3], Principle 4).

Radiological protection post-closure

3.15. Waste management facilities should be designed and operated so that radiation doses to the critical group after closure remain within an annual dose constraint, as determined by the regulatory body, which is some fraction of the dose limit for members of the public, as stated in para. 3.12. The regulatory body may also wish to specify a risk constraint for probabilistic assessments. The ICRP has recommended upper bound values of 0.3 mSv and a risk of the order of 10^{-5} per year as being appropriate [12, 13].

3.16. A combination of engineering and institutional controls (see para. 9.1) may be used to attain a level of radiological protection that meets the dose or risk constraints determined by the regulatory body. Regardless of the combination of engineering and institutional controls used, there should be reasonable assurance that these controls will remain effective for a specified period. During this period of effective engineering and institutional controls, the closed facility should meet the dose and risk constraints determined by the regulatory body. The period of institutional control should be proposed by the operator in the licensing process and supported by the safety assessment. The proposal should be submitted to the regulatory body for approval. The regulatory body's decision may be based not only on technical grounds, but also on societal considerations, and should be made on a case-by-case basis. The regulatory body should be given reasonable assurance that the controls will remain in place for the required period.

3.17. Owing to the local circumstances at many disposal facilities for mill tailings, the required periods of control may be very long or even indefinite. However, it is recognized that there cannot be absolute certainty and that there is a possibility that, over the long term, failures may occur. Therefore, designs and siting alternatives should be such that they minimize the need for active institutional controls. To ensure that this goal is met, the consequences of the failure of institutional controls and of human intrusion should be evaluated in performance assessments conducted to evaluate the designs. For the purposes of evaluating the performance of the disposal facility, the regulatory body should review the proposed period in the performance assessment calculations for which institutional controls should remain effective before failure is assumed. The impacts of the assumed failure of institutional controls and subsequent human intrusion should be taken into account in establishing the authorization for the disposal facility.

3.18. Engineering controls may fail because of natural processes (such as erosion) or events that result in the release of increased amounts of radionuclides to the environment. These events and processes are of a probabilistic nature and, for properly designed waste management systems, will have a probability of occurrence in any given year of far less than unity. They should, therefore, be treated as potential exposures, even though for assessments over very long time periods it may be assumed that some of the events will have a high probability of occurring eventually, for example, an intrusion into tailings that involves the exposure of a few individuals. Due consideration should be given to the probability of the event occurring and to its likely impact on the integrity of the disposal system.

3.19. A difficulty arises when existing waste management facilities cannot meet the post-closure risk constraints or dose constraints set by the regulatory body for new waste management facilities. As the magnitude of the assessed dose arising from intrusion increases, greater efforts should be made to make the likelihood of intrusion and/or its radiological consequences ALARA. In judging what is 'reasonably achievable' in this context, one of the primary parameters is the dose at which intervention would be considered if the event were to occur today. On the basis of current international recommendations, this value is around 10 mSv per year [2, 17].

If doses due to intrusion are likely to be below this value, then intervention is not likely to be justified. However, some States may wish to impose lower values to suit their specific circumstances. If doses due to intrusion are estimated to be higher than this value, then further efforts to reduce doses resulting from intrusion should be considered. Other parameters should also be considered in assessing what is ‘reasonably achievable’.

3.20. The primary purpose in the analysis of intrusion events is not to protect the potential intruder but to aid in the design of a resilient and stable disposal system. The closure plan should include mechanisms for preventing intrusion. Potential temporary intrusion events should be analysed to provide information for use in supporting the design of a stable disposal system. Such an analysis may also be useful in planning to minimize the consequences of temporary intrusion events.

NON-RADIOLOGICAL CONSIDERATIONS

3.21. Waste from mining and milling activities will also give rise to non-radiological hazards to humans and to the environment. Some of these non-radiological hazards will be similar to those arising from other mining and milling activities. Both radiological and non-radiological hazards should be taken into account in planning the management of this waste.

3.22. For radioactive contaminants, any chemical toxicity may cause deleterious environmental impacts at concentrations well below those necessary to produce radiological effects. Such concentrations may occur even for releases that comply with criteria established specifically for the radiological protection of humans, especially if the critical group is distant from the source.

3.23. These potential impacts should be considered at the planning stage of a mining and milling project and should be periodically reassessed throughout the project’s lifetime. Good mining practice should be followed in a manner consistent with the need for radiological protection, while it is sought to minimize the contaminant source terms, sediment loads and acid generation by means of careful design, construction, operation and closure. Any release of contaminants and sediments to the receiving environment should comply with the criteria prescribed by the appropriate regulatory body.

3.24. Various processes should be considered in assessing these impacts. For example, contaminants may be transported to the environment by seepage and surface runoff (dissolved contaminants and suspended sediments) and in mine effluents. Acid mine drainage is a particular concern with sulphidic ores. Acid generation can lead to a reduction in the pH of adjacent water systems and an increase in the mobilization of contaminants, particularly heavy metals, which may adversely affect surface water ecosystems. In addition to chemical effects, sediments arising from erosion at waste management facilities may increase turbidity or cause excessive siltation in surface water systems within the catchment area, damaging downstream ecosystems.

4. STRATEGY FOR WASTE MANAGEMENT

GENERAL

4.1. The principles of radioactive waste management set out in the IAEA Safety Fundamentals (see Ref. [3], para. 107) apply to the goals of waste management strategies for mining and milling waste.

4.2. The development of a waste management strategy is usually a complex process that has the aim of achieving a reasonable balance between two, often conflicting, goals: maximization of risk reduction and minimization of financial expenditure. The process is one of optimization of protection in which the available alternatives for siting, design and construction, operation, management of waste streams, and closure are evaluated and compared, with account taken of all associated benefits and detriments and any constraints (such as an annual dose constraint) that are required to be imposed. The characteristics of the alternatives (or options) that should be considered include:

(a) The radiological and non-radiological impacts on human health and the environment during operation and in the future;
(b) The requirements for monitoring, maintenance and control during operation and after closure;
(c) Any restrictions on the future use of property or water resources;
(d) The financial costs of the various alternatives and the resources available for implementing the alternatives;
(e) The volumes of the various wastes to be managed;
(f) The socioeconomic impacts, including matters relating to public acceptance;
(g) Good engineering practices.

4.3. The steps taken towards deciding how to manage the waste arising from mining and milling facilities should include:

(a) Definition of the criteria for human health and environmental protection;

(b) Characterization of the waste;
(c) Identification and characterization of the site options;
(d) Identification and characterization of the waste management options, including engineering controls;
(e) Identification and description of options for institutional control;
(f) Identification and description of potential failures of institutional and engineering controls;
(g) Definition and characterization of the critical group of the population;
(h) Estimation of the radiological and other consequences for each combination of options being considered (the 'safety analysis'), including scenarios of potential exposure for each option;
(i) Comparison of the estimated doses and risks with appropriate constraints;
(j) Optimization of protection so as to arrive at the preferred management option.

4.4. The evaluation criteria and procedures used to select the preferred options and to develop the waste management strategy that will achieve the optimal balance among the above considerations should be clearly defined and presented to the different interested parties in the project, including the public.

4.5. The design of mining and milling facilities will influence the optimization of protection from exposure due to radioactive waste and should therefore be considered with waste management in mind. The mining and milling activities should be designed to reduce, as far as practicable, the amount of waste to be managed. This can be accomplished through the choice of appropriate mining methods and milling processes, and the recycle and reuse of equipment, materials and waste.

4.6. The closure of the waste management facilities should be considered in all phases of the mining and milling operation, that is, during siting, design, construction and operation. Planning for the management of mining and milling waste at closure should not be delayed until the closure stage. For example, taking measures at an early stage to reduce the migration of water-borne and airborne contamination to the surrounding environment will facilitate management of the closure phase.

4.7. The design, construction, operation and closure of facilities for the management of waste from mining and milling should be in accordance with the elements of a quality assurance programme as outlined in Section 7. In particular, facilities should be constructed, operated and closed only according to approved plans and procedures.

4.8. Paragraphs 4.9–4.27 outline the important characteristics and desirable features of the options that should be considered in the siting and management of waste from mining and milling, considerations in the design, construction, operation and closure of facilities, and procedures for the release of materials.

OPTIONS FOR WASTE MANAGEMENT

Tailings

4.9. Of the different waste streams produced by mining and milling operations, tailings represent the greatest challenge, particularly in terms of long term management, because of the large volumes produced and their content of very long lived radionuclides and heavy metals. The preferred management option for achieving the protection goals will depend on specific conditions at the site, the characteristics of the ore body, the specifics of the mining and milling processes, and the characteristics of the tailings.

4.10. To conform to the principles for managing radioactive waste [3], access to and dispersion in the environment of the hazardous constituents of the tailings should be restricted for long periods into the future. The key issues which should be considered in the design of a tailings management facility include:

(a) The stability of the pit, underground mine void, or surface impoundment in relation to natural processes such as earthquakes, floods and erosion.
(b) The hydrological, hydrogeological and geochemical characteristics of the site.
(c) The chemical and physical characteristics of the tailings in relation to the potential for the generation and transport of contaminants.
(d) The volume of material that will be retained on the site as waste.
(e) The use of neutralization agents, radium precipitating additives, artificial or natural liners, radon barriers and evaporation circuits, with the reliability, longevity and durability of such agents factored in.

4.11. A thorough investigation of these issues should be undertaken at an early stage when considering options for the management of tailings. Details on the application of relevant technologies can be found in other IAEA publications [18, 19].

4.12. The design of a facility for the management of tailings should incorporate drainage systems to consolidate tailings before closure and to reduce excess pore water pressure. In the case of a surface impoundment or a pit, this could be achieved by the installation of a drainage system prior to or during the emplacement of tailings, or by the use of wicks driven into the tailings after emplacement. The base and cap of the impoundment should be built of a material of low permeability, if possible using material of natural origin. The addition of a stabilizing agent (such as cement) to the tailings immediately prior to their deposition has the potential to reduce significantly the permeability of the tailings mass, thus retarding the transport of contaminants and binding any pore water. However, in certain cases, a confined, poor quality water covering in a pit may possess excellent characteristics as a radon barrier, thereby obviating the need to perform dewatering to any significant degree. The decision on which approach to take should be optimized so as to match barrier characteristics with available site conditions. In the case of disposal in underground mines, the increase in structural integrity gained by using concrete with the tailings mass may allow mining to be continued immediately adjacent to the tailings. Prior to adopting this strategy, possible chemical interactions between the stabilizing agent, the tailings and the host rock should be carefully investigated to ensure that the transport of contaminants would not be enhanced at some time in the future.

4.13. In addition to the disposal of tailings in above ground impoundments, open pits and underground mine voids, there are other options for waste management, such as the deposition of tailings in lakes. However, some of these options may not be acceptable to regulators or the public, and would require further study and evaluation.

4.14. The principle that undue burdens should not be placed on future generations leads to the conclusion that a passive approach to design for closure is preferable to a design that needs significant and ongoing maintenance. Such a passive approach is generally best achieved by disposal in pits excavated specifically for this purpose, in mined out pits or in underground mine voids in geologically stable sites. This option may eliminate or significantly reduce the need for surface disposal of tailings. Disposal of waste below ground level is typically less susceptible to surface erosion of material to the environment and to intrusion, and generally necessitates less maintenance than surface tailings impoundments. Closure entails sealing the openings to the underground disposal facility, thereby isolating it from the surface.

4.15. For the disposal of underground tailings, provided that the probabilities of geological disturbance to the site and of human intrusion into the site are deemed to be sufficiently low, no further controls may be necessary beyond archiving details of the location and characteristics of the waste and monitoring the site for a limited period.

4.16. The passive approach to design should be considered an option more likely to be realistic in optimizing radiological protection in new waste management facilities. For example, where tailings can be deposited in mined out pits, passive designs may be partially or even fully realizable and may provide the basis for the optimum strategy.

4.17. It is possible that the underground disposal of mine tailings at a particular site may not be feasible, owing either to site specific problems for which no engineering solutions can be identified or to prohibitive cost. In such cases, the use of engineered surface impoundments may be the only viable option and should be considered.

4.18. Practical engineering solutions can be identified for some site specific problems associated with below ground level tailings disposal facilities. For example, if the hydraulic conductivity of the tailings mass is greater than that of the surrounding host rock, the use of a highly permeable envelope surrounding the tailings should be considered as a means of diverting groundwater around the tailings. In the case of a small and confined aquifer intersecting a pit or underground mine wall, localized grouting should be considered.

4.19. The desired passivity in the closure of an in-pit emplacement may be achieved either by backfilling and capping with natural materials or by the establishment of a permanent water pond over the tailings. The latter option should include the application of a low permeability cover for the waste to reduce contact with the pond water. The subsurface conditions should be fully investigated in order to gain sufficient understanding to be able to ensure that the hydraulic pressure over the backfilled pit will not result in problems of groundwater contamination arising in the future.

4.20. As regards options involving the management of tailings in above ground impoundments, the tailings should be contained within low permeability engineered structures so as to reduce seepage. An above ground closure option would usually necessitate having greater institutional control than an underground disposal option. Monitoring and maintenance programmes should be implemented during the operational, closure and post-closure phases. This approach would entail lower initial costs but higher continuing costs.

4.21. The option of relocating tailings to a more favourable site for closure would not normally be expected to provide the optimum strategy for management because of the large volumes of mining and milling waste that would be involved. However, if relocation of the waste is being considered, care should be taken to factor into the optimization all the significant radiological and non-radiological impacts that may be introduced by the relocation itself, including issues relating to the transport of large volumes of waste.

4.22. Other disposal strategies for mill tailings that take different approaches for risk assessment may be appropriate and they should be evaluated on a case by case basis. For example, small quantities of mill tailings may be acceptable for disposal in facilities designed for low level radioactive waste, provided that the waste acceptance criteria of the facility are complied with.

Other waste

4.23. Other solid and liquid wastes that are generated in the mining and milling of ores and which should be managed throughout the lifetime of the mining and milling facilities include sludges, contaminated materials, waste rock, mineralized waste rock, process water, leaching fluids, seepage and runoff. Of these other wastes, waste rock and mineralized waste rock are generally the more difficult to manage. The management of sludges and contaminated materials should be undertaken in compliance with the requirements and recommendations established in other IAEA safety standards [10, 20]. It should be ensured that all material placed in the disposal facility for tailings waste meets the closure requirements.

4.24. While the radiological hazards associated with waste rock and mineralized waste rock are usually much less significant than those for tailings, non-radiological hazards will remain and should be recognized as often being among the more important matters to be considered in the selection and optimization of management options. There are many possible options for managing waste rock and mineralized waste rock. Whichever management option represents the optimum one will depend on the particular mineralogy, radioactivity and chemical reactivity of these wastes.

4.25. Options for managing waste rock and mineralized waste rock include their use as backfill materials in open pits and in underground mines, and for construction purposes at the mine site. The need to cover mineralized waste rock with inert waste rock should be taken into account.

4.26. As with tailings, consideration should be given to the extent to which the various options will help ensure that, when managed on the surface, piles of waste rock and mineralized waste rock are stable and resistant to erosion and rainwater infiltration, and do not result in unacceptable environmental impacts on the water catchment area.

4.27. The main liquid waste will include: process water; leaching fluids; rainfall runoff from the process plant area, waste management area and ore stockpiles; seepage from mill tailings, stockpiles and waste rock disposal areas; and mine water (for example, groundwater which has entered open pits or underground mines). All liquid waste should be managed on the basis of its quality and quantity, with account taken of environmental and human health impacts, rather than on the basis of its sources. The water management system should be designed to minimize the volume of contaminated water. This could be achieved, for example, by the diversion of clean water away from sources of contamination, the reuse of wastewater in the process circuit and the use of wastewater for dust suppression.

5. SAFETY CONSIDERATIONS IN DIFFERENT PHASES OF OPERATIONS

SITING

5.1. The tailings management facility is usually located near the mill, which may be distant from the mine site. However, it is still possible, particularly for a new mine that has not yet been developed, to identify the optimum site for waste management facilities with regard to the protection of human health and the environment, and with regard to economic considerations. The siting and design of waste management facilities should provide for the effective collection and containment of waste and should prevent the diversion of waste from the site other than by means of authorized discharges or by the authorized removal of regulatory control.

5.2. A preliminary evaluation of site characteristics should be made so as to identify any restrictions, in terms of radiological and environmental factors, at each proposed location, and to allow the selection of a small number of locations and possible preliminary design concepts for which the impacts can then be evaluated in detail. The final optimized choice of site obtained using the conceptual design for waste management should be assessed and the resulting safety assessment, which might be part of the environmental impact assessment, should be submitted to the regulatory body for review.

5.3. In selecting the site for waste management facilities, the important considerations in the optimization process that should be taken into account, particularly in reducing the need for long term institutional controls after closure, include the following:

(a) Climatology and meteorology;
(b) Geography, geomorphology, demography and land use;
(c) Structural geology and seismology;
(d) Geochemistry;
(e) Mineralogy;

(f) Surface water and groundwater hydrology;
(g) Flora and fauna;
(h) Archaeological and heritage issues;
(i) Natural background levels of radiation;
(j) Public acceptance issues.

5.4. Some of these characteristics as they relate to the siting of waste management facilities and as they affect safety are discussed in Ref. [4].

DESIGN AND CONSTRUCTION

5.5. Detailed engineering design of the waste management facilities can proceed after the site and the conceptual design have been approved by the regulatory body. At this stage, a further safety assessment, including optimization of protection, should be performed. Figure 1 shows an example of the regulatory process for new facilities for the management of mining and milling waste. If significant changes are made to the design of the waste management facilities at any stage, a further safety assessment, including optimization of protection, should be undertaken.

5.6. The detailed design should be supported, where appropriate, by fieldwork and laboratory or pilot plant studies and by radiological and environmental impact assessments. The design should include a waste management plan covering the management of tailings and waste rock, effluent treatment, seepage controls and operational monitoring. The design and construction of waste management facilities should be undertaken within the framework of the quality assurance programme and should include quality control procedures. Good mining practice should be followed to the extent practicable and consistently with the requirements for radiological protection, such that the design of the waste management facilities:

(a) Maximizes the use of natural materials for containment;
(b) Maximizes the placement of waste material below ground level, or in some cases under water;
(c) Minimizes the impact on the surrounding environment during operations and after closure;
(d) Minimizes the need to retrieve or relocate the waste at closure;
(e) Minimizes the need for surveillance and maintenance during operations and for institutional controls after closure.

5.7. A preliminary closure plan should be prepared during the design of the facilities, which, at a conceptual level, identifies and ranks the available options for their closure according to the results of the safety assessment and the optimization of protection. It should also specify the financial provisions necessary for the preferred option. The preliminary closure plan should be submitted to the regulatory body for approval.

OPERATION

5.8. The waste management facilities should be operated in accordance with the waste management strategy, the safety assessment, the authorization or licence, and a waste management plan. This plan should describe in detail all aspects of the management of the waste. In addition, the plan should be consistent with the quality assurance programme and thus should include provision for:

(a) Detailed and documented procedures for operation, maintenance, monitoring, quality assurance and safety;
(b) Training of personnel in the implementation of the procedures;
(c) Adequate surveillance and maintenance of all the structures, systems and components of the waste management facility that are important to safety;
(d) A system of controlled and supervised areas and clearance procedures for materials removed from the site;
(e) Timely submissions to the regulatory body of inspection reports, monitoring results and reports on unusual occurrences;
(f) The development and exercise, where appropriate, of contingency plans for failures of the waste management facilities that may result in a significant reduction in the protection of human health or the environment.

5.9. Measures should be taken during operations, and consistently with the safety assessment, to limit the rates of release to the environment of contaminants in liquid and airborne effluents [21]. Measures should be used to ensure that solid waste remains under proper control so that the misuse of tailings is avoided. Releases of radon or radioactive dusts into the atmosphere and of radium and other radionuclides into surface water and groundwater by surface runoff or leaching from solid waste should be minimized.

CLOSURE

5.10. The preliminary closure plans should be revised periodically during the operation of the waste management facilities to reflect significant operational changes, technological advances and regulatory requirements. The financial mechanism(s) guaranteeing that funds will be available to fulfil the requirements for closure and post-closure should be updated as necessary. Updated plans and financial mechanisms should be evaluated by the regulatory body.

5.11. Once any part of the waste management facilities is no longer needed, it should be closed to the extent practicable during operations (e.g. closure of a waste rock pile).

5.12. At a time agreed upon with the regulatory body, and at least five years before the anticipated closure date, the operator should submit a final closure plan for regulatory approval. The objectives of closure should be to ensure that the waste management facilities are left in a condition that will ensure their continued compliance with the requirements for the protection of human health and the environment.

5.13. The closure plan should be harmonized to the extent practicable with the schedule for decommissioning surface structures and equipment. The decommissioning of these structures and equipment has been addressed in other IAEA safety standards [1, 10]. The management of waste from decommissioning activities may be combined with management of the closure of the facilities for the disposal of waste from operations, provided that this will not introduce problems, for example, by creating voids in the tailings mass. This is most effectively accomplished when decommissioning is conducted prior to, or at the same time as, closure.

REMOVAL OF REGULATORY CONTROL

5.14. Prior to the release of material, equipment, structures or the site to the public for general or restricted use, regulatory criteria should be established, such as those for:

(a) Removal of material, equipment, structures, soil and rock, from regulatory control;
(b) Authorized reuse or recycle of equipment, structures and material;
(c) Release of the entire site for authorized use (depending on future plans) at the end of closure.

Each of these sets of criteria should be established on the basis of realistic exposure scenarios.

5.15. Guidance on removal from regulatory control and on cleanup levels can be found in Refs [17, 22, 23].

6. SAFETY ASSESSMENT

GENERAL

6.1. The safety assessment should indicate how the waste management facilities should be designed to provide optimum protection to workers, the public and the environment. A safety assessment should be prepared and updated as necessary by the operator in support of applications to the regulatory body for approvals to develop, operate or modify facilities for managing waste from mining and milling. A safety assessment should also be prepared in a timely manner for existing facilities, if none is available.

6.2. The safety assessment should cover the operational, closure and post-closure phases of the facility. The scope and extent of the assessment should be commensurate with the site specific issues that should be addressed. The results of the initial safety assessment should be factored into the choice of site and the design of the mining and milling facilities. The assessment should consider all significant scenarios and pathways by which workers, the public and the environment may be subject to radiological and non-radiological hazards. Where possible, and where warranted by the significance of potential impacts, this assessment should be quantitative. The scope and depth should be sufficient to be able to identify and evaluate all relevant risk components over the relevant periods of the facilities' lifetimes. The models and methods used should allow the effects of the various hazards in the different management options to be compared in a consistent manner.

6.3. In the safety assessment, all the waste management facilities at the site should be considered together with those features of the mine and mill and of any other nearby facilities that may influence the methods available for managing the waste. The safety of the waste management system together with that of the mine and mill as a whole should be optimized. The assessment will be an iterative one, analyses being refined and models and input information updated as the process proceeds from development of the concept through design, construction, operation and closure.

6.4. All steps in the safety assessment will entail handling uncertainties in the input information. These arise from:

(a) Approximations inherent in modelling complex systems;
(b) Limitations in the understanding of the processes that determine the behaviour of the site and the waste management system and uncertainties in the relevant parameters;

(c) Uncertainties in the relevant future conditions (for example, demographic conditions, the effectiveness of institutional control, climatic conditions) over long periods;
(d) Uncertainties about the likelihood and magnitude of external events such as earthquakes and floods that could affect the integrity of the waste management systems.

6.5. These uncertainties should be assessed and carried through the assessment so that the robustness of the conclusions drawn from the assessment is evident.

6.6. Some of the uncertainties can be reduced, though not eliminated, by better site characterization, by refining models or by obtaining more site specific data. The regulator should decide which sources of uncertainty need to be addressed in the safety assessment, in particular those that will need to be considered into the far future.

SAFETY CRITERIA

6.7. Following the recommendations made in Section 3, criteria should be specified for the radiological protection of workers during operations and of the public for the releases that occur during operations and for those that are expected to occur after closure. The criteria for the protection of the environment against radiological and non-radiological hazards should also be defined. The appropriate regulatory body should determine all these criteria prior to assessment of the proposed waste management system.

CHARACTERIZING THE WASTE

6.8. The waste that will be generated in the mining and milling operations should be properly defined on the basis of the operating process and the characteristics of the site. Items that should be considered include the type of waste, the volumes expected, chemistry issues and minerals in the waste. Further recommendations and guidance and considerations in the characterization of the waste are presented in Refs [18, 24].

IDENTIFYING AND CHARACTERIZING SITE OPTIONS

6.9. Potential sites for mining and milling waste should be selected on the basis of the considerations outlined in Section 4. The characteristics of the potential sites would determine the generation of contaminants and their transport from the sites. These characteristics should be determined and the appropriate source term models and contaminant transport models, and their associated parameters, should be specified.

6.10. Baseline environmental data should be collected before operation of the waste management facility has commenced. These data should be used, as appropriate, for the calibration and validation of models and to establish reference levels for monitoring and surveillance activities during all phases in the lifetime of the waste management facility. The average values for, and the ranges in background levels of, radioactive and non-radioactive contaminants for locations at and around the sites of the proposed waste management facility should be determined.

6.11. If the facilities are in operation, the site and its environment should be characterized as soon as possible. The main characteristics to be evaluated should be similar to those used for the baseline survey.

IDENTIFYING AND CHARACTERIZING OPTIONS FOR WASTE MANAGEMENT, INCLUDING ENGINEERING CONTROLS

6.12. Potential options for managing the waste should be identified according to the considerations outlined in Section 5. A broad range of options should be considered for the initial analysis. The behaviour of the various options for managing the waste should be modelled using appropriate models and parameter values.

IDENTIFYING AND DESCRIBING OPTIONS FOR INSTITUTIONAL CONTROL

6.13. The operator should determine which institutional controls may be applicable after closure of the waste management facility and should describe their key characteristics, including the period over which they may be assumed to remain effective. These controls should be proposed to the regulatory body and should be reviewed as part of the closure plan. Guidance is provided in Section 3.

IDENTIFYING AND DESCRIBING POTENTIAL FAILURES OF INSTITUTIONAL AND ENGINEERING CONTROL

6.14. In order to estimate potential exposures, possible future events that could give rise to increased risks should be considered. Such events, which include failures of institutional and engineering controls, fall into the following categories:

(a) Human activities (for example, intrusion, farming, building on areas where waste was previously managed, unauthorized diversion and use of radioactive waste);
(b) Natural processes and events that may affect the integrity of containment structures (for example, erosion, flooding, earthquakes);
(c) Internal processes (for example, acid generation, weathering effects, failure of the containment slope, differential settlement).

6.15. As noted in Section 3, it may be appropriate to assume that institutional controls will prevent human intrusion and inappropriate use of land for a certain period of time. The operator should recommend establishment of such a period as part of the overall closure plan and it should be approved by the regulatory body. The period over which engineering controls are assumed to remain effective should be based on a technical assessment in which account is taken of factors such as erosion, seismology, hydrology, hydrogeology, acid generation, and other physical and chemical processes that may affect the integrity of engineered structures or the release of radionuclides from waste to the environment. Appropriate models describing these failures should be developed for input into the safety analysis.

SAFETY ANALYSIS

6.16. The safety analysis is part of the overall safety assessment. Safety analyses should be carried out to estimate occupational exposures, public exposures and environmental impacts. In the case of public exposures, the safety analysis should quantify the incremental exposures due to the waste in excess of the exposure due to natural background levels of radiation. These analyses should be reiterated as the options for siting, management, and institutional and engineering controls are refined. A safety analysis should include, as appropriate:

(a) Consideration of all relevant radionuclides, chemical and physical processes of concern, pathways and exposure scenarios so as to provide the basis for comparison with dose and risk constraints and environmental protection criteria;
(b) Consideration of events, including their probabilities, that could lead to a release of radionuclides or other contaminants, or that could affect their rates of release or their rates of transport through the environment;
(c) Estimation of radiation doses likely to be received by workers during operations;
(d) Estimation of radiation doses and risks to members of the public, and specifically to the critical group, by different pathways, and estimation of environmental impacts during operations and after closure;
(e) Analysis of uncertainties and sensitivities, as appropriate, in order to determine the potential origins of the greatest risks.

6.17. In the case of exposures arising during operation and after closure, it is usually sufficient to consider scenarios and make assumptions that are based on the lifestyles and living conditions of individuals residing in the general vicinity of the waste management facilities.

COMPARING ESTIMATED DOSES AND RISKS WITH CONSTRAINTS

6.18. For each site, there will be one or more options for management of the waste. Each of the waste management options will have a range of appropriate institutional and engineering controls. For each of these institutional and engineering controls, there will be particular ways in which they may fail, each with particular implications. The doses (and risks, as appropriate) for each of the combinations discussed above should be compared with the appropriate constraints for the operational and post-closure phases as indicated in Section 3. Combinations of options that exceed a constraint should be set aside. The others should be considered in the optimization analysis (see Fig. 2 for an illustration of this process).

6.19. In the case of existing waste management facilities, one or more of the constraints may be exceeded for every practicable combination of options considered. In identifying the preferred option in the optimization analysis, the failure of an option to meet one or more of the constraints should be taken into account. Section 3 provides guidance for cases such as this.

OPTIMIZING PROTECTION

6.20. Protection is optimized when any additional efforts to control doses would not be warranted by the further reduction in doses that would be achieved. For protection of the public, the combinations of waste management options that would meet the appropriate dose or risk constraints as discussed in the foregoing should be examined on this basis.

6.21. There are several decision aiding techniques that can be applied (outlined in paras 6.22–6.24). The technique chosen should be appropriate for the complexity of the particular case being assessed and for the number of factors that the regulatory body decides should be taken into account.

6.22. If the cost associated with the different options is the only factor to be considered, then a quantitative cost benefit analysis may be used. In this case, the following should be considered:

(a) Time period over which the radiation doses and other impacts are to be integrated (account being taken of the period over which meaningful predictions are possible);
(b) Spatial cut-off points of the areas within which impacts are considered;
(c) Monetary value of reductions in risks to humans and in environmental harm (for radiological risks, the monetary value of averting a unit of collective dose).

6.23. The collective dose may not always be a significant factor or attribute in the evaluation of disposal options. In such cases, critical factors or attributes will drive the decision. For these more complicated analyses, different decision aiding techniques should be used. Examples include multiattribute utility analysis and multicriteria outranking analysis. Similar considerations should apply for optimizing the protection of workers [25].

6.24. The results of a safety assessment and the conclusions of a subsequent optimization process should be examined for their stability with regard to the uncertainties involved. Guidance on how to carry out uncertainty analyses and sensitivity analyses may be found in Refs [26–28].

7. QUALITY ASSURANCE

7.1. It is required that a quality assurance programme be implemented throughout the design, construction, operation and closure of waste management facilities so as to ensure that radiological and non-radiological protection will be maintained during their operation and to enhance confidence in protection after their closure [2], [10] para. 7.6, [29].

7.2. The quality assurance programme should, as a minimum, include the following:

(a) Organizational responsibilities should be defined and understood.
(b) Design and construction should employ proven technology that conforms to approved national codes and standards.
(c) Regular auditing of the design, its implementation and the operation of the waste management facilities should be undertaken in order to ensure that they are designed, constructed and operated as intended, and that deficiencies can be corrected.
(d) Models and codes used in the safety assessment should be validated and verified to the extent possible.

(e) A feedback process should be established and the results of the safety assessments should be taken into account appropriately during the design. There should be close co-operation among all parties involved in the development of waste management facilities in order to reach the optimum solution.
(f) Everyone involved in the design, construction, commissioning, operation and closure of waste management facilities and whose performance could influence safety should be trained to an appropriate and verified level.
(g) A system of record keeping and document handling should be established in order to retain appropriate details of construction and operation, including monitoring data, and to control changes in operations.
(h) The effectiveness of the protection achieved in the management of waste should be assessed periodically.

7.3. The organization(s) with overall responsibility for operation, post-operational activities, closure and institutional control should also be responsible for establishing and implementing any quality assurance programme.

8. MONITORING AND SURVEILLANCE

8.1. A monitoring and surveillance programme should be developed as early as practicable and, subject to the approval of the regulatory body, should be implemented by the operator at all stages during the lifetime of the waste management facilities. Records of the results of the programme should be maintained in a form readily amenable to interrogation [5, 19, 25]. The programme should be managed in accordance with the elements of a quality assurance programme as described in Section 7. The monitoring and surveillance programme should be reviewed periodically and also following any major changes in waste management operations or in regulatory requirements.

8.2. The goals of a monitoring and surveillance programme should include:

(a) Establishment of baseline or current conditions;
(b) Provision of site specific input for use in the safety assessment of the proposed designs;
(c) Verification of compliance with regulations, discharge authorizations and procedures;
(d) Provision of data from which radiation doses to workers and to members of the public from exposures due to the waste management facilities may be assessed;
(e) Verification of the effectiveness of engineering designs;

(f) Calibration and validation of models and verification of their predictions;
(g) Provision of data for possible revisions to discharge authorizations;
(h) Establishment of conditions that would trigger non-routine investigations and/or inspections and preparation for dealing with such conditions;
(i) Detection of environmental impacts;
(j) Verification of the physical condition and integrity of the waste management facilities.

8.3. The monitoring and surveillance programme for a particular waste management facility should be based on the safety assessment and account should be taken of site specific factors (e.g. climate, site location, geological conditions, design of the facilities, off-site environment, population distribution).

8.4. Radionuclides that will be released from the facility are also present in the natural environment (the background). The doses due to exposure from each of these two sources (radionuclides from the facility and radiation from the natural background) should be determined in order to judge whether the release of radionuclides due to activities at the facility complies with appropriate criteria.

8.5. The monitoring and surveillance programme should specify the parameters to be monitored, the locations and frequencies for sampling and data logging, and the procedures for reporting and analysis. The programme should also set investigation and/or action levels for certain key parameters so that appropriate and timely action can be taken if monitoring reveals a significant deviation from what is expected or acceptable. Such a monitoring programme should include measurement of:

(a) Indicators of environmental impacts, such as levels of radionuclides and non-radiological contaminants in air, water and soil;
(b) The physical integrity of structures and systems for waste containment;
(c) Parameters that may assist in the interpretation of data such as meteorological data, operational process data and waste stream data.

8.6. The monitoring programme for occupational radiation protection during the operational phase of waste management facilities is usually a part of the general monitoring programme for occupational radiation protection at the mine and mill. A special monitoring programme for occupational radiation protection may be required for the closure and post-closure phases of the waste management operation.

8.7. The regulatory body should be provided at intervals with the results obtained from an approved monitoring and surveillance programme, in the form stipulated by the regulatory body. The regulatory body should develop and undertake its own monitoring programme in order to verify the validity of monitoring reports provided by the operator.

8.8. For a number of years after the closure of waste management facilities, the operator should normally be required to demonstrate that the facilities are performing as predicted in the design. To demonstrate this, an appropriate monitoring and surveillance programme should be implemented after closure. Details of the content and application of post-closure monitoring and surveillance programmes for above ground designs are provided in Refs [19, 30].

8.9. Baseline data collected prior to the development of waste management facilities should be used to provide a reference by which the results of post-closure monitoring can be compared. This will be particularly valuable if the regulatory body has stipulated closure requirements in terms of incremental changes permitted in parameters rather than by setting absolute limits.

8.10. Prior to termination of the operator's responsibility for closed waste management facilities, the operator should provide the regulatory body with the results of a final radiological and environmental survey and a closure completion report in order to document compliance with the regulatory requirements for managing the waste.

9. INSTITUTIONAL CONTROL FOR THE POST-CLOSURE PHASE

9.1. Institutional control consists of those actions, mechanisms and arrangements implemented so as to maintain control or knowledge of a waste management site after closure, as required by the regulatory body. This control may be active (for example, by means of monitoring, surveillance, remedial work, fences) or passive (for example, by means of land use control, markers, records).

9.2. Establishment of the requirements for institutional control should be a part of the optimization of the design for closure. The need for, and dependence on, active institutional controls should be minimized in the design.

9.3. The programme for institutional control should be reviewed by the regulatory body so as to verify its effectiveness. The design of the programme should be based on the safety assessment in which impacts on human health and the environment over an appropriate period into the future should be considered. The operator should determine the period over which institutional controls can be assumed to remain effective and this should be approved by the regulatory body. Scenarios postulating human intrusion, failure of engineered structures and developments in the environment, as discussed in Section 3, should be considered in the safety assessment.

9.4. As part of an institutional control programme, all relevant records of the location and characteristics of closed waste management facilities, restrictions on land use and ongoing monitoring and/or surveillance requirements should be maintained in accordance with applicable legal requirements. Legal provision should be made for the regulatory body to withdraw or modify components of the institutional control programme, as deemed appropriate in the light of results of monitoring and surveillance. Information on the site, the required institutional controls and the rationale or need for such controls should be documented and made publicly available.

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