Decommissioning of Facilities for Mining and Milling of Radioactive Ores and Closeout of Residues

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1994
DECOMMISSIONING OF FACILITIES
FOR MINING AND MILLING OF RADIOACTIVE ORES
AND CLOSEOUT OF RESIDUES
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DECOMMISSIONING OF FACILITIES
FOR MINING AND MILLING
OF RADIOACTIVE ORES
AND CLOSEOUT OF RESIDUES

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1994
FOREWORD

Mining and milling of radioactive ores result in contaminated buildings and facilities that should be decommissioned, as well as large quantities of tailings and other residues that should be managed safely so that residual environmental and health risks do not exceed acceptable levels. The technical aspects related to the safe management of mill tailings are given in IAEA technical reports such as Current Practices for the Management and Confinement of Uranium Mill Tailings, Technical Reports Series No. 335 (1992), and Measurement and Calculation of Radon Releases from Uranium Mill Tailings, Technical Reports Series No. 333 (1992). Safety aspects related to this subject are addressed in an IAEA safety standards document entitled Safe Management of Wastes from the Mining and Milling of Uranium and Thorium Ores, Code of Practice and Guide to the Code, Safety Series No. 85 (1987).

During the 1980s, many uranium mines/mills were closed. More are being closed as uranium production becomes unprofitable because of lower prices resulting from a decrease in demand and an abundant supply and, to a certain extent, because of the higher cost of providing measures that are consistent with society’s current expectations in environmental protection. During the 1980s, considerable experience was accumulated on the decommissioning of mine/mill facilities and the closeout of tailings impoundments. In response to this wealth of information and the needs of Member States, the IAEA felt that preparation of a report focusing on the decommissioning of uranium mine/mill facilities and the closeout of tailings and other residues should be initiated.

This report was first drafted in 1990 with the assistance of consultants from Australia, Canada, Spain and the United States of America; P.L. De was the IAEA Scientific Secretary. The report was redrafted in 1991, with the assistance of two consultants from France and the USA, and subsequently reviewed at a Technical Committee Meeting in April 1992. The report was finalized by incorporating comments from members of the Technical Committee and edited by the IAEA Scientific Secretary, M. Laraia, of the Division of Nuclear Fuel Cycle and Waste Management, with the assistance of M.A. Feraday, Canada.

The IAEA wishes to express its gratitude to those experts who contributed to the development and completion of this report.
EDITORIAL NOTE

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**CONTENTS**

1. INTRODUCTION .......................................................... 1

2. PURPOSE ........................................................................ 3

3. SCOPE ........................................................................... 3

4. OBJECTIVES OF DECOMMISSIONING/ CLOSEOUT PROGRAMMES .............................................. 4

5. REGULATORY CONTROL FOR DECOMMISSIONING/CLOSEOUT .............................................. 5

5.1. Fundamental principles .................................................. 6

5.2. Safety analysis and safety assessment ............................. 7

5.2.1. Introduction ............................................................ 7

5.2.2. Pathway analysis ..................................................... 9

5.2.3. Optimization .......................................................... 11

5.2.4. Uncertainty and variability in input parameters .......... 12

5.2.5. Probabilistic and deterministic analyses .................... 13

5.2.6. Acceptability criteria and standards ......................... 14

6. SITE CHARACTERIZATION .................................................. 15

6.1. Site characterization for construction licence application .......... 15

6.1.1. General requirements ............................................. 16

6.1.2. Baseline environmental data .................................... 17

6.2. Site characterization for decommissioning/closeout ............ 18

6.2.1. Operational phase characterization studies .................. 18

6.3. Selection of an alternative waste management site ............ 20

7. PLANNING AND TECHNICAL CONSIDERATIONS ......................................................... 21

7.1. Planning for the decommissioning/closeout ..................... 23

7.1.1. Initial conceptual planning ....................................... 23

7.1.2. Ongoing planning .................................................. 23

7.1.3. Final detailed planning .......................................... 23

7.2. Decommissioning of mine/mill buildings and facilities ........ 24

7.2.1. Planning considerations .......................................... 24

7.2.2. Technical considerations ........................................ 25
7.3. Decommissioning/closeout of uranium mines ........................................ 27
  7.3.1. Planning considerations .......................................................... 27
  7.3.2. Technical considerations ......................................................... 27
7.4. Decommissioning/closeout of tailings impoundments ............................. 30
  7.4.1. Planning considerations .......................................................... 30
  7.4.2. Technical considerations ......................................................... 34
7.5. Decommissioning/closeout of mining debris piles ................................ 36
  7.5.1. Planning considerations .......................................................... 36
  7.5.2. Technical considerations ......................................................... 37
7.6. Decommissioning/closeout of heap leach piles ................................... 38
7.7. Decommissioning/closeout of in situ leaching operations ....................... 39
7.8. Cleanup of vicinity properties ...................................................... 40
7.9. Restoration of site ........................................................................... 41
7.10. Remediation of groundwater ............................................................ 41
7.11. Improvement in the decommissioning/closeout plan/design .................... 41
  7.11.1. General technical planning considerations .................................... 41
  7.11.2. Effective methods for improving the plan/design ............................ 42
8. IMPLEMENTATION OF THE DECOMMISSIONING/
   CLOSEOUT PLAN ......................................................................................... 44
  8.1. General ......................................................................................... 44
  8.2. Decommissioning of mine/mill buildings and facilities ......................... 46
  8.3. Decommissioning/closeout of uranium mines ...................................... 47
  8.4. Decommissioning/closeout of tailings impoundments ........................... 47
    8.4.1. Stabilization in place with covers ............................................. 48
    8.4.2. Relocation of tailings to an alternative site ................................. 48
  8.5. Decommissioning/closeout of mining debris piles ................................ 49
  8.6. Decommissioning/closeout of heap leach piles ................................... 49
  8.7. Decommissioning/closeout of in situ leaching operations ....................... 50
  8.8. Cleanup of vicinity properties ....................................................... 51
  8.9. Restoration of site ........................................................................... 51
  8.10. Remediation of groundwater .......................................................... 52
9. RADIATION PROTECTION, HEALTH AND SAFETY
   PROGRAMMES DURING DECOMMISSIONING/
   CLOSEOUT ACTIVITIES ........................................................................... 52
  9.1. Dust control ..................................................................................... 53
  9.2. Air and water sampling ..................................................................... 53
  9.3. Radiation monitoring ........................................................................ 54
  9.4. Traffic control .................................................................................. 54
10. POST-CLOSEOUT MONITORING AND SURVEILLANCE PROGRAMMES ........................................ 54

10.1. Baseline data ................................................. 55
10.2. Pathway analysis ............................................ 56
10.3. Post-closeout monitoring/surveillance programme ........................................ 56
   10.3.1. Water quality monitoring ............................. 57
   10.3.2. Atmospheric monitoring .............................. 58
   10.3.3. Rehabilitation surveillance .......................... 60
   10.3.4. Biological monitoring ............................... 60
10.4. Post-closeout institutional controls ........................................ 60

11. COST ESTIMATING AND FINANCING FOR DECOMMISSIONING/CLOSEOUT .................................. 61

11.1. Financing alternatives ...................................... 61
11.2. Decommissioning/closeout costs ................................ 61

12. DOCUMENTATION FOR DECOMMISSIONING/CLOSEOUT .......... 62

13. QA PROGRAMME FOR DECOMMISSIONING/CLOSEOUT ...... 63

13.1. Organization .................................................. 64
13.2. Design control ............................................... 64
13.3. Instructions, procedures and drawings .......................... 64
13.4. Document control ............................................. 64
13.5. Materials, parts, components and samples .......................... 65
13.6. Inspection .................................................... 65
13.7. Test control .................................................. 65
13.8. Non-conformance ............................................. 65
13.9. QA records ................................................. 65

14. SUMMARY AND CONCLUSIONS .................................. 66

14.1. Summary ...................................................... 66
14.2. Conclusions .................................................. 66

ANNEX I: EXAMPLES OF NATIONAL REGULATORY REQUIREMENTS, REGULATIONS AND CRITERIA FOR MILL TAILINGS AND THE DECOMMISSIONING/ CLOSEOUT OF URANIUM MINES/MILLS ......................... 69

Example 1: EPA standards, USA ............................................ 70
Example 2: Generic requirements of the regulatory authorities in Canada ................................................................. 72
Example 3: French regulations: Decree No. 90-222 dated 9 March 1990 .. 74

ANNEX II: EXAMPLES OF NATIONAL CRITERIA FOR THE EXEMPTION, RELEASE OR CLEANUP OF RADIOACTIVE SITES, BUILDINGS, EQUIPMENT AND MATERIALS FROM THE DECOMMISSIONING/CLOSEOUT OF URANIUM MINES/MILLS ........................................... 77
Example 1: French exemption levels adopted for specific decommissioning projects ............................................ 78
Example 2: NRC: Acceptable surface contamination levels for uranium and thorium ........................................... 79
Example 3: NRC: Cleanup criteria for land and soil ......................... 80
Example 4: Canadian mine/mill material salvage decontamination limits ... 80
Example 5: Recommendations of the SKK (Germany) concerning the release of solid materials in the decommissioning of uranium milling facilities .................................................. 81

ANNEX III: GEOTECHNICAL, HYDROLOGICAL, ENVIRONMENTAL AND ECONOMIC RATING MATRIX ......................... 87

ANNEX IV: CHECKLIST FOR REVEGETATION OF DECOMMISSIONED URANIUM TAILINGS ......................... 97

ANNEX V: LONGEVITY REQUIREMENTS ........................................... 99

ANNEX VI: NATIONAL EXPERIENCE IN THE DECOMMISSIONING/ CLOSEOUT OF FACILITIES AND RESIDUES FROM THE MINING AND MILLING OF RADIOACTIVE ORES .................. 103
Australia .............................................................................. 104
Canada ............................................................................. 118
China ............................................................................... 126
France ............................................................................. 131
Germany .......................................................................... 138
Slovenia ........................................................................... 145
Spain ............................................................................... 151
United States of America ...................................................... 157
1. INTRODUCTION

Some 420 nuclear power plants with a total output of more than 330 000 MW(e) of electrical power are currently in operation and more are being constructed or planned [1]. A large number of uranium mine and mill facilities have been developed to produce the uranium required to fuel these power plants [2]. These mines and mills, and the large volume of residues produced during their operation, will have to be decommissioned/closed out when the facilities have reached the end of their useful life.

Mining and milling residues are the solid and liquid wastes left over from the mining and milling of ores to recover uranium [3]. The major solid residues are uranium mill tailings; mining debris, including barren rock and low grade ore; residues from heap leaching; and scrap material and equipment from maintenance and decommissioning [4]. Similar wastes are produced during the mining and milling of thorium ores to recover rare earths and other metals; however, the volume of thorium tailings is relatively small when compared with that from the milling of uranium ores.

Mill tailings are the most important solid waste residues resulting from the mining of uranium ores for nuclear power plants. It has been predicted that about 500 GW(e) of nuclear generating capacity will be in service in the world some time after the year 2000 and that the total uranium needed by then would be about 2 million tonnes. If this uranium were produced from 0.1% uranium ore, some 2000 million tonnes of uranium mill tailings would be left behind for disposal, plus large quantities of material that is below ore grade and other mining debris. The tailings inventory would be accumulating at the rate of some 75 million tonnes per year at mine/mill sites throughout the world [5]. These tailings differ from those arising from the mining and milling of most other metal bearing ores by having greater residual radioactivity.

Recently, the need to develop proven methods and techniques for decommissioning/closeout of uranium mine/mill facilities has taken on added importance. During the 1980s and early 1990s, many older uranium mines were closed because of a decrease in the demand for uranium and an increase in the overall supply. The resulting low prices and the cost of providing the extra measures needed to satisfy society's higher expectations in the area of environmental and radiological protection made production of uranium unprofitable for many low grade mines.

For example, four uranium mine/mill facilities (Quirke, Panel, Denison and Stanrock) near Elliot Lake in Canada, the Ecarpierre mine in France and the Freegold uranium recovery plant in South Africa have been closed down in the last few years. The Mount Taylor mine in New Mexico, United States of America, was allowed to flood following unsuccessful attempts to sell it. These examples of closure, which are not exhaustive, total over 3500 t U, or about 10% of the 1989 production of the
region formerly known as the World Outside Centrally Planned Economic Areas (WOCA).

Following political changes in eastern Europe, production of uranium in Bulgaria, the former Czechoslovakia, Hungary and Romania is being reduced as delivery contracts with the former Union of Soviet Socialist Republics are terminated. The most extensive shutdowns occurred in the former German Democratic Republic. As of the end of 1990, conventional mining operations at five uranium mines and two mills in Germany have ceased.

Although some of these mines/mills will probably reopen when demand and prices increase, many will be shut down permanently and have to be decommissioned/closed out.

In the past, some mines, mills and tailings areas have either been abandoned or decommissioned/closed out in a way that might pose continuing adverse impacts to the health and safety of people and the environment. This resulted from a lack of suitable regulations and a poor understanding of the hazards of tailings and confinement technology. Regulatory bodies in many countries are now seeking ways of remedying the situation.

At present, new and operating mine/mill facilities typically have a number of licence conditions and regulations related to health, safety and protection of the environment. Inspections and monitoring operations by the regulatory authorities, to ensure compliance with the licence conditions, are conducted routinely. Adoption of effective measures by the industry, to limit adverse environmental and health effects, has demonstrated that uranium mining and milling and the management of uranium tailings can be carried out safely and with acceptable impacts during the operational life of a project.

For facilities that were built earlier and are still operating, the licence conditions should be modified to ensure that human health is protected and that the environmental effects in the long term, post-operational phase are acceptable.

In IAEA usage and current public understanding, the term decommissioning as related to nuclear facilities means that the site or cleaned up facility will ultimately be released for unrestricted use, with no further requirement for regulatory control after completion of the work. A facility or site can be decommissioned by decontaminating it to acceptable levels and/or by dismantling it and disposing of all contaminated materials in a waste repository.

In this context, the buildings, equipment and physical plant associated with a mine or mill facility could be decommissioned using currently available methods. Even a tailings impoundment could, in principle, be decommissioned by removing the tailings to an impoundment at another location and cleaning up the original site. However, the quantity of uranium tailings involved in most tailings impoundments, among other factors, may preclude relocation as a cost effective option.

Most tailings impoundments are closed out after they have been rehabilitated as necessary to bring them up to the required regulatory standards. Closeout con-
notes a requirement for long term institutional (regulatory) control. The common objective of decommissioning or closeout is to modify the site or facility so that the resulting social, health and environmental impacts are limited.

2. PURPOSE

The purpose of this report is to provide information to Member States in order to assist in planning and implementing the decommissioning/closeout of uranium mine/mill facilities, mines, tailings impoundments, mining debris piles, leach residues and unprocessed ore stockpiles.

Although many IAEA reports have been published to provide information [3, 6–8] and guidance [4, 9–11] to Member States for the mining and milling of radioactive ores, mill tailings management and the decommissioning of nuclear facilities [12–19], none has been written on the decommissioning/closeout of uranium mine/mill tailings facilities. The present report covers the latter topics.

3. SCOPE

The report presents an overview of the factors involved in planning and implementing the decommissioning/closeout of uranium mine/mill facilities. The information applies to mines, mills, tailings piles, mining debris piles and leach residues that are present as operational, mothballed or abandoned projects, as well as to future mining and milling projects. The report identifies the major factors that need to be considered in the decommissioning/closeout activities, including regulatory considerations; decommissioning of mine/mill buildings, structures and facilities; decommissioning/closeout of open pit and underground mines; decommissioning/closeout of tailings impoundments; decommissioning/closeout of mining debris piles, unprocessed ore and other contaminated material such as heap leach piles, in situ leach facilities and contaminated soils; restoration of the site, vicinity properties and groundwater; radiation protection and health and safety considerations; and an assessment of costs and post-decommissioning or post-closeout maintenance and monitoring needs.

In this report, the terms decommissioning and closeout are intended to cover all the actions necessary to enable a site or facility to meet the radiological criteria for either unrestricted use or long term closeout under institutional control, and to enable the owner/operator to be released from the ongoing responsibility of caring for the site.
The report does not deal with the following options related to the long term management of mill tailings because of the limited applicability of the methods:

(1) Dispersal of tailings into the environment at a safe rate, as agreed between the operators and the competent authority. In some Member States, owing to difficulties in finding suitable materials for rehabilitation work as well as financial constraints, and taking into account weather conditions and the availability of deserted land, it has been proposed that tailings be dispersed in a controlled manner. This option is highly site specific in that it uses existing site characteristics, e.g. dilution capabilities.

(2) Extracting contaminants from tailings to permit more secure disposal of a much smaller volume of contaminated waste.

The report mainly discusses uranium mine/mill facilities. However, most aspects apply also to the mining and milling of thorium bearing minerals. Where appropriate, reference to thorium specific aspects is made throughout. Much of this report may also apply to mines and mills extracting uranium or thorium as a by-product, as well as to non-uranium mines and mills where significant quantities of radionuclides of the uranium or thorium decay chain are present.

Although the report deals mainly with radioactive pollutants in mill tailings, non-radioactive pollutants such as sulphides and heavy metals might be the main environmental concern in setting the disposal standards, and might even be the prime determinant in a programme. However, the designs and engineering technology used to confine the radioactive pollutants in uranium mill tailings are usually more comprehensive than those used in other sectors of the mining industry and should safely confine non-radioactive pollutants.

4. OBJECTIVES OF DECOMMISSIONING/CLOSEOUT PROGRAMMES

The major objective of decommissioning at a uranium mine/mill complex is the decontamination/dismantling of sites, buildings, structures and equipment so that the items can be reused/recycled, if appropriate, or sent for disposal in an approved facility. A secondary objective of decommissioning is the demolition of inactive buildings/facilities associated with the mine/mill complex if these are not required and it is deemed that they could be a hazard in the future.

The major objective related to the closeout of impoundments for tailings or other large quantities of radioactive residues is to ensure that retaining structures meet the regulatory/design requirements; isolate wastes for a reasonably long period
of time; and restrict the release rate of pollutants from the containment to the environment to acceptable levels, while minimizing reliance on active and passive institutional controls for the protection of public health and safety and the environment.

The common objective of decommissioning/closeout is to modify the site or facility so that the resulting social, health and environmental impacts are reduced to acceptable levels.

Whether decommissioning or closeout is the appropriate action for mining debris, mines and heap leach residues and in situ leaching facilities will depend on factors such as the amount of waste, the residual radioactivity, the site characteristics and the requirements of the regulatory authority.

5. REGULATORY CONTROL FOR DECOMMISSIONING/CLOSEOUT

Most Member States of the IAEA have a national nuclear policy and the laws, competent authorities, regulations and research to implement the policy and to regulate nuclear facilities and the use of radionuclides in industry, medicine and research. Development of a strategy for the decommissioning/closeout of shut down mine/mill facilities should be undertaken within the framework of this nuclear policy.

Decommissioning of the buildings, structures and equipment associated with a uranium mine/mill facility can be carried out using the regulations, planning, equipment and methods employed for the decommissioning of other nuclear facilities [12–19]. These facilities could be decontaminated for unrestricted release and/or demolished and the contaminated residues sent for active disposal.

However, the decommissioning/closeout of the mine and the storage/disposal facilities for contaminated waste, especially mill tailings, require special consideration. Mines can be closed out, either empty or filled with tailings and other debris, by sealing the openings. Waste management facilities can only be closed out after the containment structures meet regulatory standards.

Safety analyses should be carried out to determine the short and long term consequences (risks) to humans and the environment associated with the proposed decommissioning actions and the closed out facilities. These risks are then compared (in a safety assessment) with the regulatory criteria and requirements for the closeout of the mine and tailings impoundments and the cleanup of the site to determine if the risks are acceptable. If they are not acceptable, then further improvements are made to the design and the consequences reassessed.

In this section, the fundamental principles for closeout, the regulatory safety analysis/assessment process and aspects of these assessments are addressed briefly.
5.1. FUNDAMENTAL PRINCIPLES

The proposed decommissioning/closeout actions will give rise to radiological/toxic chemical risks in both the short and long term. In the short term, risks may arise from the activities associated with the execution of the remedial programme. In the long term, risks arise from events such as human actions associated with intrusion into tailings or removal of contaminated material; migration of contamination via wind/water pathways; and migration of the waste as a result of failure of the containment structures.

Although short term risks associated with the remedial work may be relevant to both workers and the general public, long term risks are usually limited to the general public and the environment.

To ensure that these risks are adequately controlled, Member States should have a regulatory body with the authority, funding and regulations required to control the decommissioning/closeout of mine/mill complexes in a safe manner. The

![Diagram of safety assessment process](image)

**FIG. 1.** Process of safety assessment of a shallow ground disposal system. (Taken from Ref. [20], with slight modifications.)
regulatory authority assigned this responsibility should establish fundamental safety standards and criteria against which the acceptability of the remedial action can be judged.

Examples of national regulations and criteria related to the decommissioning/closeout of mine/mill facilities are given in Annex I. In applying these regulations, remedial approaches different to those taken for current and future facilities may need to be considered for abandoned mine/mill facilities.

The primary requirement of the regulatory process is to ensure that risks remain within acceptable levels. Ideally, in exercising regulatory control, regulators should also aim to ensure, where possible, that the closeout regulations/criteria for tailings impoundments are site specific and flexible; to achieve a situation where unrestricted access is allowable to as many of the facilities as is economically justifiable; to allow for unrestricted or restricted release/reuse of as much material and equipment as is economically justifiable; and to reduce the need for institutional control as far as possible: if institutional control is required, active operational control, e.g. long term effluent treatment, should be minimized rather than passive control, e.g. control of land use.

Owing to the nature of mining and milling activities in general, practical and economic realities may not enable the complete achievement of these objectives. Depending on national regulations and on the project in question, the regulatory process often requires an optimization exercise to support the selected remediation options.

5.2. SAFETY ANALYSIS AND SAFETY ASSESSMENT

5.2.1. Introduction

To ensure that the risks associated with a closed out facility meet the regulations and criteria, a quantitative safety analysis/assessment should be carried out. The assessment methodology can be generic or site specific.

In the context of this report, a safety analysis is the process of analysing and calculating the hazards (risks) associated with a closed out mine/mill facility. The methodological approach most frequently used in safety analyses of disposal facilities consists of performing scenario analyses in which release and transport scenarios for radioactive and toxic pollutants are defined quantitatively, followed by consequence analyses in which the radiological consequences of releases to the environment are calculated using mathematical models [20].

In a safety assessment, the results of the safety analysis (risks to humans and the environment) are compared with the regulatory criteria to determine if the releases from the facility are acceptable. Figure 1 shows how the scenario and consequence analyses interact and how they fit into the safety assessment [20]. The figure
also shows the iterative nature of safety analyses/assessments. It is important to emphasize that the closed out facility and its environment should be analysed as a system.

In summary, steps in the safety analysis/assessment approach are:

1. To define the radionuclide and chemical waste source term in the facility under study and the condition of the waste
2. To define the waste and its barriers and the near field geosphere at the site
3. To define the release scenarios and pathways (subsection 5.2.2) from the closed out waste to the environment and humans and the probability of occurrence of each scenario
4. To determine and analyse the consequences (risks) of the releases to humans and the environment
5. To compare the consequences (risks) of the releases with the acceptability criteria and decide if the risks are acceptable.

The safety analysis/assessment process requires that the terms of these steps be detailed, translated into mathematical terms and incorporated into predictive models. This analytical process is described in more detail in Refs [3, 4, 7, 8, 20–23].

If the risks to humans are shown to be unacceptable, then the proposed closeout design for the facility should be improved to reduce releases and another assessment made. The risk associated with the revised closeout option should then be assessed to test its compliance with established individual dose or risk limits and be used as input into the subsequent optimization study.

Generic safety analyses/assessments can be used to establish numerical criteria that could be used at all sites (see Annex I). This approach can also be useful in evaluation of a preliminary design when first formulating a disposal facility, where criteria are established for a notional facility in an environment defined by generic characteristics. In this situation, conservative assumptions are used so that there is some assurance that the design will meet the regulatory limits and criteria for most sites. When first formulating the design for a new disposal facility, the preliminary design is often assessed for a hypothetical site until the final site is selected.

The advantages of the generic approach to setting criteria are that it provides clear requirements to both operator and regulator and that similar technical solutions can be applied to all facilities. The main disadvantage is that the requirements may be more stringent than those needed for a site having characteristics that are more favourable than those of a generic model. The generic approach necessarily precludes optimization.

The site specific methodology assesses the actual risk associated with the site. This allows specific controls to be established from the site in question in order to demonstrate compliance with the risk criteria laid down.
The site specific safety analysis/assessment has the advantage that the risk associated with a particular facility located on a specific site can be quantified and an optimum remediation option selected. In cases where there is a major variation in site specific parameters, this approach may be the only one possible. A site specific assessment is more complex than a generic assessment; it provides data on which optimization of the actual design can be accomplished (subsection 5.2.3).

In addition to radiological hazards, the release of non-radioactive toxic materials into the environment from a closed out facility may be of concern. Regulatory procedures that address these issues should be available. An integrated site specific assessment of risks resulting from radiological and chemical pollutants may be feasible and desirable. The topic of non-radioactive pollutants is discussed in more detail in Ref. [3].

These assessments can only provide estimates of the magnitude of the risks to humans and the environment because of uncertainty and variability in the input parameters (subsection 5.2.4).

5.2.2. Pathway analysis

Radioactive and toxic chemical contaminants released to the environment may result in exposure to humans through various physical, chemical and biological processes. These processes include the release and transport of contaminants into the environment by air and water pathways; the uptake or bioaccumulation of contaminants by local plants and animals; and the factors related to the living conditions or life-style of the exposed individual [3].

Important release mechanisms include spills during transport of waste; radon emanation; wind/water erosion or dispersion; failure of containment structures; controlled/uncontrolled release of contaminated water; groundwater seepage/dispersion; and unauthorized removal of waste [3].

This section gives a brief description of the major pathways by which these released pollutants can reach the environment and humans. Pathway analysis is important during every stage in the life-cycle of a mine/mill facility, from initial licensing and design to post-closeout monitoring.

Exposure pathways (Fig. 2) may be generalized as follows [3]:

1. Atmospheric pathways that lead to irradiation by inhalation of radon and its daughters, inhalation of airborne radioactive particles and external radiation
2. Atmospheric and terrestrial pathways that can cause doses resulting from ingestion of contaminated foodstuff and external irradiation
3. Aquatic pathways that can result in dose exposure from the ingestion of contaminated water, foods produced using irrigation, or fish and other aquatic biota, and from external irradiation.
FIG. 2. Generalized source, environmental transfer and dose model [3]. (Dotted lines indicate pathways that are not usually explicitly modelled, but are implicitly included in other modelling.)
These processes are highly site specific and time dependent. For example, both contaminated dust particles and radon gas are contributors to the final dose dispersed through the air. However, the air pathway is more significant than the water pathway at arid sites, and in desert like conditions it is the predominant pathway. At sites where annual precipitation is high enough to result in surface water systems, the water pathway can become significant and may predominate. Saturated tailings, however, are less likely to cause dust and radon problems via the air pathway.

5.2.3. Optimization

Optimization should not be restricted to the remediation of abandoned mining and milling facilities. Rather, operating mining and milling facilities should also be involved in detailed planning and optimization of their decommissioning, closeout and remedial actions.

Selection of an optimum option requires that all the detriments and benefits associated with the option be identified, as far as possible, and assessed. These include items such as radiological impact; conventional safety and toxic chemical impact; long term monitoring, maintenance and active operational control; restriction on the further use of property or affected water supplies; financial costs of various alternatives; and public involvement in the proposed remedial action.

The optimization process has two components: engineering optimization and radiological optimization [23]. In engineering optimization, subsystem targets are reviewed to determine if they can be relaxed to allow less costly designs that will still enable the total system target to be met. Radiological optimization reflects current radiological principles which require that, for any level of predicted radiological impact, the financial and other costs of further impact reduction must be quantified in order to determine if further reduction is worthwhile. Eventually, the predicted radiological impact of the selected option must be less than the regulatory limits.

Two approaches to optimization are generally considered: differential cost–benefit analysis and multi-attribute analysis [3]. In quantitative cost–benefit analysis, radiological optimization of a tailings impoundment or other mining and milling residues needs to take into consideration the following [24]:

1. The time period over which the collective dose commitment is to be integrated (taking into account the time over which meaningful predictions can be made)
2. The spatial cut-off point within which the critical group or person can be identified
3. The monetary value of the unit collective dose
4. More than one optional and comparable protection plan
5. The cost of implementation of each comparable option
6. Pathway analysis to determine the dose commitment resulting from each of the options under consideration.
Further discussion and illustration of the differential cost–benefit techniques can be found in greater detail in Refs [5, 25, 26].

Multi-attribute analysis permits consideration of factors that are not treated in the cost–benefit analysis. The objective of the multi-attribute analysis is to construct a scoring system for alternatives, so that the alternative with the highest score is preferred [3]. Although this type of optimization has been used for radiological impacts, the process can be used for the hazardous non-radiological substances associated with mill tailings and other mining and milling residues. Guides on this technique are given in Ref. [27].

5.2.4. Uncertainty and variability in input parameters

The difficulties in carrying out a safety analysis are the uncertainties inherent in the process and the variability in input parameters.

5.2.4.1. Uncertainty

In safety analyses, uncertainties are usually due to:

1. The ability of the models to represent the system completely
2. The current understanding of the whole closed out facility/site system, and of how and when the containment structures might fail
3. The limited knowledge of future demographic and climatic conditions over long periods of time
4. The poorly defined values of input parameters for predictive models; also, owing to the long term nature of the risks, estimates have to be made for future long term changes in parameters and processes
5. The occurrence of low probability/high consequence events such as earthquakes, cyclones, hurricanes, tidal waves, floods and human intervention.

In view of such uncertainties, there can be a tendency to incorporate conservative assumptions, which lead to overestimates of exposure in safety analysis. Care must be taken to avoid introducing so large a bias that the predicted dose is an inaccurate estimate of risk from the proposed activity.

Uncertainty analysis is used to quantify the extent to which the predicted performance of the system may differ from the actual performance as a result of uncertainties in data input.

Sensitivity analysis is used to evaluate the influence of changes in the value of one or more input parameters on the results of the calculation.

Guidance on how to carry out uncertainty and sensitivity analyses may be found in Refs [22, 23, 28].
5.2.4.2. Variability in input parameters

Risk prediction is dependent on natural factors such as the climatic conditions, soil properties and hydrological conditions, all of which can be highly variable. The parameters related to natural factors may vary from site to site, with seasons and with location on a site. They can be estimated in terms of probability distribution functions.

Many other factors relevant to the long term integrity of confinement systems are also probabilistic in nature, e.g. earthquakes or floods. The occurrence and intensity of such events can only be assessed by probabilities (e.g. maximum earthquake magnitude or flood intensity that is likely to occur within a reference time period).

Owing to the complexity of natural systems, it is not possible to address all relevant processes in a risk assessment. For example, the factors that determine the migration of contaminants through soil are an extremely complex combination of chemical and physical processes, forcing modellers to use simplifications [3]. However, a simplification can sometimes overcome the complexity and simultaneously yield a conservative outcome. In the case cited above, contaminant transport in soil, an assumption that contaminants migrate at the same rate as water, will simplify all modelling and provide a conservative risk estimate.

The risk assessment should address both deterministic and probabilistic aspects (subsection 5.2.5), the latter to take into consideration, inter alia, containment structure failure, earthquakes, floods, etc.

Once the optimal decommissioning/closeout options have been identified by either the generic or the site specific approach, the regulatory authority should mandate their implementation, if they are acceptable.

5.2.5. Probabilistic and deterministic analyses

Mathematical models and analytical techniques for safety assessment can be divided into probabilistic and deterministic analyses [20]. These are complementary techniques and, as a general rule, both are used in scenario and consequence analyses.

Scenario analysis is mainly and necessarily probabilistic because the probabilities of occurrence of various events and processes should be taken into account. However, it also has deterministic components, since submodels must be used to predict the effects of various events and processes and, hence, to provide input data for the release and transport calculations.

An example of the use of a probabilistic model is given in Ref. [3]. The calculated risk estimates are statistical distribution functions, which give the probability of occurrence of risk levels. This type of result will answer questions such as: What is the maximum risk (dose) to an individual based on a certain probability?
Consequence analysis is primarily deterministic because its main objective is calculation of the rates of radionuclide release and transport and subsequent doses to humans; models are usually deterministic. However, if there are uncertainties in the release and transport parameters, the distribution functions of these parameters are used in the calculations to obtain ranges of dose. In this situation, for consequence analysis it is necessary to use probabilistic (statistical) as well as deterministic techniques.

In simpler deterministic modelling, conservative estimates can be used for all processes and parameters that are subject to variations or uncertainties. Careful determination of these estimates will ensure that the calculated doses are within the prescribed limits.

One advantage of a probabilistic approach is that the model keeps track of variations and uncertainties; this is particularly important in complex situations. If, for example, a certain risk is determined by ten parameters, setting all parameters very conservatively would lead to an extreme overestimate of risk, because a coincidence of conservative values is likely to have a very small probability.

5.2.6. Acceptability criteria and standards

In the decommissioning/closeout of mine/mill complexes, regulatory acceptability criteria or standards are required for handling those items that still contain some residual radioactivity; examples of these criteria are:

1. Cleanup criteria for the site that define the specific radionuclide concentration limit or gamma exposure level which must be achieved by workers doing specific remedial work
2. Criteria for the release of the whole site for restricted or unrestricted use (depending on future plans) once the whole cleanup programme is completed
3. Criteria for the unrestricted release of material, equipment, soil, rock, etc. that have contamination levels which are below regulatory concern; criteria for restricted release of equipment and reusable material may also be required.

Regulatory authorities may establish levels for surface contamination or specific activity that give rise to levels of risk which are 'below regulatory concern' and do not warrant further control. Examples are exemption criteria for equipment, scrap or building debris intended to be reused or recycled and waste material intended to be disposed of at conventional waste sites.

The basic principles on which exemption of sources or practices from regulatory control is based have been established [29]. However, these principles still leave room for different practical interpretations in terms of derived levels (surface activity, mass activity); indeed, regulatory practices still differ widely among countries. Also, in many countries decisions to release material are still taken on a case by case basis.
Examples of national practices for the unrestricted release of materials from decommissioning operations are provided in Refs [12, 13] and in Examples 1–5 of Annex II [30–33].

The radionuclides of concern in mine/mill facilities are natural constituents of many materials, e.g. soil and building materials. The soil around a near surface uranium mine often contains significant concentrations of uranium and its daughters. In many cases, this situation causes great difficulties in discriminating between artificial contamination and natural background. This is of particular importance if remediation targets are based on regulatory criteria that address only the man-made portion of radioactive concentrations or radiation doses.

In addition to exemption levels, it may be appropriate to establish criteria for the handling of radioactive equipment and other materials, and their disposal in locations such as tailings impoundments, mining debris piles and mines.

In considering which activities should be subject to regulatory control, it is of benefit to the regulatory authority to specify the appropriate reference levels. One example would be the specific activity levels in the soil below which no restrictions on land use are necessary. In addition, it may be possible to specify levels that would allow land to be used for specified purposes (e.g. industry or recreation).

An important aspect in the application of these generic criteria is that their derivation is necessarily based on conservative assumptions. Exceeding such criteria would not automatically give rise to unacceptable risks. Actual risks can only be assessed on the basis of situation specific analysis.

6. SITE CHARACTERIZATION

For a mine/mill complex, site characterization could be required:

(1) For site acceptance during the original licensing of the mine and the associated facilities (subsection 6.1)
(2) For assistance in developing the overall decommissioning/closeout plan (subsection 6.2)
(3) For selection of an alternative disposal site for mill tailings and other mine/mill residues (subsection 6.3), if an alternative site is required.

6.1. SITE CHARACTERIZATION FOR CONSTRUCTION LICENCE APPLICATION

The location of a mine is determined by the geology and natural occurrence of the ore body. For the purpose of this subsection, it is assumed that the size, mine-
ralogy and ore grade have been characterized in sufficient detail to warrant development of the mine. The following subsections deal with the additional characterization that is required in support of the initial licence application.

6.1.1. General requirements

In addition to characterization of the ore body, detailed characterization of the surrounding area is required to assist in the siting of facilities such as the mine access, impoundments for tailings and other residues, mill, administration and health facilities and possibly a town site; and in the collection of baseline environmental data (subsection 6.1.2), including a radiological, chemical and ecological database for the area, for use in the final closeout of the site, post-closeout monitoring (Section 10) and other operations.

The types of general programme/information required during the initial site characterization could include:

(1) Aerial photographic reconnaissance to provide an overview of the topography and the geomorphic and surface water features; geological discontinuities such as faults might also be detected
(2) A detailed visual survey of the site to define topographical characteristics such as gullies, slopes and other features of the district
(3) Gamma, alpha and beta surveys to determine the nuclide specific background radiological characteristics
(4) Documentation of the local ecosystem, identifying critical components such as endangered species and the biological monitoring opportunities
(5) The climatic data for the region
(6) Geological, geotechnical and geophysical data such as the properties of the rocks, the geological structure and stratigraphy, the erosion characteristics, the lithology and mineralogy, the soil strength, the clay and silty sand content, the tectonics and seismicity, the potential for flooding and erosion, and the logging and monitoring programmes to establish the potential stability of the containment structures, tailings and mining debris piles
(7) Hydrogeological and hydraulic characterization of the area to determine:
   (a) The groundwater quality/quantity, flow rates, depth to water table, hydraulic gradients, recharge/discharge areas, sorption characteristics, etc.
   (b) The surface water quality, runoff, evapotranspiration and data on surface water bodies such as lakes, ponds, rivers and creeks, as well as the drainage sediment quality
(8) Assessment of social issues, e.g. determination of the presence of historical/archaeological artefacts, endangered species, employment opportunities, land use, scenic values, potential for other viable uses, etc.
Much of the geological and hydrogeological data could be obtained through subsurface investigations using boreholes, monitoring wells and test pits in soil and bedrock to establish area and vertical profiles of the hydrogeological regime and soil and bedrock conditions, and to obtain soil, rock and groundwater samples for chemical contaminants and radiological analyses.

6.1.2. Baseline environmental data

Baseline environmental data should be collected during the pre-operational stage of a mine/mill facility, before beginning major site activities. These measurements can be used as reference levels during cleanup associated with the decommissioning/closeout phase and for post-operational monitoring and surveillance activities (subsection 10.3). Usually, these data are collected as input for environmental impact assessment associated with the licence application.

During baseline monitoring, every effort should be made to measure both the average values and the range of background levels for radioactive and toxic contaminants at and around the sites of the proposed mine/mill complex. These data will make it easier to select appropriate and defensible cleanup criteria. Public concern over the adequacy of cleanup criteria can sometimes be reduced if these are related to the baseline background levels.

Selection of the parameters to be surveyed depends on local characteristics. However, relevant information would include the radionuclide and toxic chemical concentrations; the soil, rock and water parameters relevant to the retardation/leaching of contaminants; and local ecosystem data.

The most expensive data gathering activity may be the drilling of boreholes and the sampling of these bores for potential contaminants. Borehole drilling should be done in a systematic manner, based on a methodology using random selection of borehole locations. However, consideration should also be given to establishing at least some boreholes for long term monitoring in areas where contamination is more likely to occur. The number of boreholes drilled and samples taken should be based on the level of uncertainty and the degree of complexity of the potential site. After the first data gathering, additional data gathering may be required to answer new questions that develop during the initial drilling programme.

Statistical aspects play a major role in site characterization. For example, a statistical methodology to determine an optimum soil sampling strategy for detecting/delineating uranium mill tailings spread from storage piles by wind is illustrated in Ref. [34].

Details on the site characterization needs and data collection techniques can be found in IAEA reports [35, 36] and in a report from a Member State [37], respectively.
6.2. SITE CHARACTERIZATION FOR DECOMMISSIONING/CLOSEOUT

In establishing a decommissioning/closeout plan for a mine/mill complex, the existing characterization data from the original licence application (subsection 6.1) and from subsequent design phase and operational phase characterization studies (subsection 6.2.1) should be co-ordinated and evaluated.

The following actions are needed to provide for the development of a comprehensive decommissioning/closeout plan for a mine/mill complex:

1. Identification and characterization of those areas on the site and the adjacent properties which require cleanup
2. Evaluation of the long term suitability of existing sites of tailings impoundments and other waste storage areas
3. Assessment, if necessary, of alternative sites for waste disposal (subsection 6.3 describes one approach for selecting an alternative site)
4. Development of any necessary additional characterization studies for the site.

It is generally known which facilities, structures, buildings, etc. must be decontaminated and dismantled and which waste management areas must be closed out. However, the characteristics of sites for the mill tailings impoundments and other waste management areas may or may not be well known, depending on when these facilities were built and on the regulatory requirements at that time.

The regulatory objectives or criteria for post-closure cleanup and acceptable site conditions should be known before additional site characterization is initiated, since the requirements specified for an acceptable site could affect the characterization programme. This applies whether the mining/milling residues are to be stabilized in place, on-site, or are to be relocated to a new disposal site.

The successful rehabilitation of a mine/mill complex area can best be achieved if, from the time of the initial project planning, all operations are planned and carried out to meet the requirements for final site rehabilitation. If not, rehabilitation will usually involve additional effort and be more expensive.

6.2.1. Operational phase characterization studies

After the decommissioning/closeout requirements have been established, existing operational data and records should be evaluated in conjunction with the characterization data from the original licence application (subsection 6.1) and the design phase characterization studies to determine which of the following operational data are relevant:

1. **Mining operations**: The number of mines; characteristics of the ore bodies, including size, mineralogy and grade; mining methods; sequence of operations; rates of production of barren wastes, contaminated wastes and ore; location of the mill site with respect to the mines, tailings impoundments, mining
debris, leftover ore, etc.; and the health/environmental effects and mobility of contaminants. In addition, the amount of ore body that remains in the mine should be determined.

(2) **Milling operations:** The chemical, physical and radioactive properties of the wastes; and the mobility of the contaminants and their health/environmental hazards.

(3) **Site and other data:**

(a) Identification of all plant, mine and waste management areas, affected infrastructure and confirmed or suspected areas of on-site or off-site impact

(b) An inventory of all systems, facilities and installations at each plant, mine or waste management site

(c) A description of all areas and their location, and the classes of environmental concern, e.g. low and high level radiological contamination; controlled and hazardous substances and products; non-radioactive wastes; effluent discharge areas; areas contaminated by stack emissions

(d) Detailed maps of the mine/mill facility and its environs

(e) Changes in the surface water and groundwater characteristics since the original characterization studies

(f) An inventory of receptors and potential pathways

(g) A reassessment of the pertinent geochemical, geotechnical and geological characteristics.

All these data should be evaluated to determine what additional data, if any, are required to implement the decommissioning/closeout programme so that the regulatory standards applicable to the site (Section 5) are met. The final data evaluation stage normally includes:

(i) Preparation of radiological and chemical contaminant distribution reports for on-site and off-site areas

(ii) Evaluation of the results of contaminant and waste identification surveys and assessment of the mine/mill facilities

(iii) Evaluation of the stability and condition of all waste management and disposal areas

(iv) Evaluation of the local and regional geological and hydrogeological conditions and of the groundwater/contaminant migration potential from the sources of radioactive and chemically hazardous materials and wastes associated with discharges from the mines, mills, waste management and disposal areas

(v) Modelling of contaminant transport

(vi) Risk assessment and development of site specific cleanup criteria, where necessary (see Section 5)

(vii) A decision whether or not an alternative site is required for the management of the mill tailings and other residues.
6.3. SELECTION OF AN ALTERNATIVE WASTE MANAGEMENT SITE

During planning for the shutdown of a uranium mine/mill complex, a reassessment of the waste management areas for tailings and other toxic mining residues may indicate that the sites are not suitable for long term management, or effective rehabilitation of the impoundment is too costly or not achievable. In this case, an alternative site may have to be selected so that the wastes can be relocated. Such conditions may be more common for older facilities, where the siting and design of impoundments were not as well regulated or understood as at present and decommissioning/closeout was not considered.

In many Member States, relocation to an alternative site is not practical and other engineered solutions have to be found.

If relocation of the waste is required, the procedures for selecting a new site can be found in Refs [35, 36, 38]. An example of a five phase procedure [38] for selecting a new site is presented below.

During Phase I, an initial search region, including lands within a specified radial distance of the mine or the current location of the waste (for example, a 10 km radius), is initially selected. The factors to be considered include local and state preferences, the likelihood of finding suitable sites and other appropriate factors. If no suitable sites are found in the initial search area, then the region is enlarged and the evaluation process repeated.

During Phase II, areas unsuitable for waste disposal or long term storage are eliminated using screening guidelines that are based on geotechnical, geological, hydrological, seismological and environmental factors and are developed by a team of experts. The guidelines are used to eliminate broad areas from consideration. An intensive data gathering programme to develop new information is not envisaged during this phase. Regional screening guidelines would typically exclude as sites those areas near geological faults or saturated loose sands susceptible to liquefaction; areas with known erosive soils or significant recoverable mineral resources; areas adjacent to lakes, rivers or wetlands; areas over aquifers having drinking quality water; areas in a floodplain, e.g. a 500 year flood plain; areas near subsidence zones, or archaeological or historical resources; areas of prime farmland; and locations adjacent to wildlife refuges or human communities.

During Phase III, several of the candidate sites not eliminated during Phase II are selected for further analysis on the basis of factors such as transportation routes and accessibility; terrain; nearby structures; potential borrow sites for cover material; flooding potential; geomorphic stability; aquifer parameters (e.g. quality, volume, depth, direction); subsoil geochemical properties; potential impacts of waste disposal on groundwater; fault zones; recent seismic activity; erosion potential; liquefaction potential; slope stability; and distances from critical habitats, prime farmland and cultural resources.
During Phase IV, a field inspection and drilling/test pit programme would be instituted to obtain information on the selected sites, for example, thickness of soils; depth to groundwater; relative contaminant attenuation capacity; and other hydrological and geological data. The number of boreholes drilled and test pits dug should be the minimum required to obtain the necessary information for decision making.

In Phase V, the sites are ranked on the basis of their characteristics in four areas: geotechnical, hydrological, environmental and economic. Each characteristic is weighted according to its importance and a point score is obtained for each site. This allows a quantitative judgement to be developed for the selection of a site. For example, the major geotechnical factors include distance to the nearest seismic risk fault; geomorphic stability; the relative strength and compressibility of the foundation soil and rock; and susceptibility to slope failures and subsidence. The major hydrological factors include the background water quality; the aquifer volume yields; and the geochemical properties of the aquifer and subsoils. The major environmental factors include the presence of threatened or endangered species and the distance to the nearest point of groundwater withdrawal from the potentially affected aquifer. The economic factors include the distance of the proposed disposal site from the existing site, the means of transport and the accessibility [38].

Annex III gives an example of a phased, site selection approach as used in the USA for the Uranium Mill Tailings Remedial Action (UMTRA) Project.

7. PLANNING AND TECHNICAL CONSIDERATIONS

Planning for the decommissioning/closeout of new uranium mine/mill facilities should start during the design and construction phase and continue with progressive refinement of the plans during the operational phase. This planning should culminate in the successful implementation of an optimized decommissioning/closeout plan that is approved by the regulatory authority, takes into consideration the site specific aspects, and ensures protection of the health and safety of humans and long term protection of the environment.

The decommissioning/closeout of a mine/mill complex can best be addressed on a site specific basis because of the diversity of site conditions and the magnitude of operations; the variety of mining methods, e.g. underground or open pit; the different extraction processes, e.g. acid, alkaline and solvent; and the range of proposed uses for the site.

Local factors such as national priorities, climate, meteorology, hydrology and the potential for flooding are likely to have a great effect on decommissioning/closeout planning. Issues dominant at one site may be unimportant at other sites, for example, precipitation. While the experience of others is valuable, practices,
standards and criteria accepted elsewhere for the design or performance of work should not be adopted from one site to another without assessment and optimization.

Although it is more cost effective to preplan and engineer for decommissioning/closeout before a mine/mill facility is commissioned, this was not always done for older facilities. Preliminary conceptual decommissioning/closeout plans for these operating facilities should be prepared and approved by the regulators as soon as possible.

The decommissioning/closeout of a mine/mill complex can often be accomplished by a variety of approaches, for example:

(1) An underground mine may be sealed as is to allow flooding, if this is possible, or be filled with tailings or mining debris before sealing
(2) Tailings may be stabilized in place or, occasionally, be relocated
(3) Materials and equipment from the dismantling of mine/mill buildings and structures may be decontaminated for unrestricted or restricted release, or be disposed of at an appropriate location on-site or off-site.

The technical options, methods and equipment used should be the best available, taking into consideration what must be done, the protection of humans and the environment, and the economic and social factors.

Of the available options, only those that result in acceptably low individual doses should be considered. Use of optimization techniques should aid the choice between various options. Two important approaches to the optimization of radiation protection are differential cost–benefit analysis and multi-attribute analysis. The basic methodology of the two approaches is presented in Ref. [4]. An illustration of application of the differential cost–benefit technique to the management of wastes from uranium mining and milling is presented in Refs [5, 25]. Applications of the multi-attribute technique are described in Ref. [38].

Factors relevant to the planning, information requirements and technical considerations for decommissioning/closeout of various facilities at a mine/mill complex are presented in the following subsections; implementation of these plans is discussed in Section 8:

(a) Subsection 7.1 reviews the overall sequential planning associated with all parts of the mine/mill complex and outlines in general terms the contents of a detailed plan that would be submitted in support of the licence application to decommission/close out the facilities
(b) Subsections 7.2 to 7.7 review the specific planning and technical considerations relevant to the decommissioning/closeout of various parts of the mine/mill complex
(c) Subsections 7.8 to 7.10 discuss the cleanup of vicinity properties, restoration of site and remediation of groundwater, respectively
(d) Subsection 7.11 reviews the improvement in decommissioning/closeout plan/design.
7.1. PLANNING FOR THE DECOMMISSIONING/CLOSEOUT

Ideally, planning for the decommissioning/closeout of all parts of a mine/mill complex should start before the facility is commissioned and should encompass three phases: initial conceptual planning, ongoing planning and final detailed planning.

7.1.1. Initial conceptual planning

In many Member States, a conceptual decommissioning/closeout plan for a new uranium mine/mill facility must be submitted to the regulatory authority before the construction licence is issued. This plan should show that the proposed approach is, in the light of existing knowledge, safe, technically feasible and financially responsible. It should also present the ways in which the long term health and safety of humans and the environment will be protected, socioeconomic considerations taken into account. This plan should indicate how the proponent will ensure that financial resources are available to complete the required work.

Licensees of existing facilities not having a conceptual decommissioning/closeout plan should develop such a plan and submit it to the regulatory authority without undue delay.

7.1.2. Ongoing planning

During the operation of the mine/mill, the preliminary plan should be reviewed and updated periodically to reflect changed circumstances and socioeconomic conditions, modifications of operational procedures, advancements in technology, or the factors affecting financial assurances.

7.1.3. Final detailed planning

When the date and circumstances of the final shutdown of a facility are known, a detailed plan in support of the application for a licence to decommission/close out a facility or site should be submitted to the regulatory authority for approval before the scheduled end of operations. The plan should include the following information:

1. A description and operational history of the buildings, facilities and waste piles to be decommissioned or closed out
2. A summary of the relevant site characterization data available (subsections 6.1 and 6.2), including the results of surveys for radiological, chemical and other contaminants present on surfaces, in air and in water
3. The identity of adjacent properties or water bodies that will require remedial cleanup
The proposed starting date and time schedule for the proposed actions
A summary of the national and regional legal, regulatory and safety requirements
The rationale for selecting the proposed decommissioning or closeout option and for rejecting alternatives
The quantity, type and radiation level of the radioactive substances present at the facility
Details of those chemicals and minerals present which may influence the release of radioactive substances from the disposal areas
A description of the expected radioactive and other hazardous wastes resulting from the decommissioning/closeout actions and of the proposed plans for recycling, reusing and/or disposing of the wastes or equipment
A quality assurance (QA) programme relating to health, safety and environmental protection (Section 13)
The proposed plans for radiation protection, health and safety programmes (Section 9), post-closeout monitoring and surveillance programmes (Section 10), and cost estimating and financing (Section 11)
A description of the contingency measures to be taken to limit the hazards resulting from unplanned events during decommissioning/closeout
Safety, performance and environmental analyses and assessments examining the impacts of the proposed work on the health and safety of humans and the environment, and the measures that would be used to keep adverse effects within limits
A description of the credentials, experience, resources and responsibilities of the organization(s) doing the decommissioning/closeout work
Other information that the regulators may require to evaluate the application with respect to the health, safety, security and protection of the environment.

The regulatory authority should use inspections and other means to follow the progress of work at the site(s) and, when appropriate, issue complementary licences, approvals, regulations, instructions or comments. Figure 1 in Ref. [19] shows regulatory interfaces in the decommissioning of major nuclear facilities. Long term considerations that affect the environment and the health and safety of the public should be taken into account in the plans.

7.2. DECOMMISSIONING OF MINE/MILL BUILDINGS AND FACILITIES

7.2.1. Planning considerations

The regulatory approach, much of the planning and safety guidance, and the methodology and technology used to decontaminate and dismantle equipment, pip-
ing, ducts, buildings, etc. in other nuclear facilities such as power plants, reprocessing plants and fuel fabrication facilities can also be used to plan and implement these tasks in all parts of a uranium mining and milling complex [12-19, 39]. This would include items such as head frames, elevators, ore transport systems, ventilation ducts, surface buildings, tanks, mill equipment and piping.

7.2.2. Technical considerations

Owing to the very long half-lives of some isotopes present in the uranium decay chain, there are no radiological reasons for delaying the dismantling of uranium mine/mill facilities to allow for the decay of radioactivity.

Once the mine/mill buildings have been decontaminated as required and dismantled, the technical options for managing materials and equipment still having residual contamination are as follows:

1. Decontaminate valuable equipment/materials for unrestricted use and/or remove them to another site for restricted use
2. Place the remainder of the contaminated equipment/materials in the tailings impoundment, underground mine, open pit mine or specially prepared pit for disposal
3. Dispose of the uncontaminated equipment/materials at a conventional waste disposal site or at an approved location on-site.

7.2.2.1. Decontamination of equipment/materials for unrestricted or restricted use

The activities required to decontaminate equipment/materials and verify that they are radiologically suitable for unrestricted use are generally labour intensive and expensive. The economic viability of releasing these items for unrestricted use may also be affected by the lack of potential customers and a low market value for the salvaged material [12].

Suitable decontamination techniques include vacuuming, scrubbing, pressurized water or steam jetting with or without detergents, and sandblasting [16, 18]. Wash water may be recycled. The planning, statistical methods, operating procedures and monitoring equipment used to ensure that materials/sites released for unrestricted use comply with release criteria are discussed in Refs [12, 13, 29].

Slightly contaminated mining and milling equipment, motors, tools and valuable materials are often moved to other nuclear facilities for restricted reuse or recycling. These items would be cleaned to remove loose contamination before shipment.
7.2.2.2. Disposal of contaminated equipment/materials

If unrestricted/restricted release of equipment/materials is not the preferred option or is not economically viable, and the equipment cannot be decontaminated to activity levels that are below regulatory concern, the following wastes can generally be placed in an impoundment, mine or specially engineered pit on-site: parts of buildings, equipment and scrap with contaminant concentrations that are not below regulatory concern; sludge or consolidated liquid/evaporated residual waste with elevated metal and radionuclide concentrations; and asbestos or other toxic materials.

The volume of contaminated equipment/materials placed within the tailings impoundment and/or mine should be of such a quantity and should be distributed in such a manner so as not to jeopardize the long term stability and integrity of the impoundment or permit unacceptable migration of the contaminants into the environment.

Improper placement of large quantities of organic materials and large pieces of metal, stone and/or concrete demolition debris into the tailings impoundment may cause problems such as differential settlement and damage to dams or liners. Care should be exercised in the placement of such materials in order to minimize such effects.

7.2.2.3. Disposal of uncontaminated equipment/materials

Equipment/materials that are inactive or have radioactivity levels or other containment levels that are below regulatory concern can be disposed of at a conventional waste disposal site or an approved location on-site. These materials may include low leachability materials from the demolition of office and administrative buildings and parking lots. They may be placed on a heap using less stringent handling, cutting and placement procedures and less critical cover and erosion protection than those used for contaminated waste.

7.2.2.4. Management/disposal of liquid waste

The following technical alternatives may be considered for the management/disposal of liquid waste from decommissioning:

1. Evaporation/treatment and subsequent disposal of the sludge within the tailings impoundment, underground mine, open pit mine or specially prepared pit
2. Solidification in cement or other matrix and subsequent disposal
3. Transfer to another acceptable site
4. Dilution and dispersal with appropriate controls, e.g. use of pre-release biological toxicity testing to assess safe dilution ratios.
7.3. DECOMMISSIONING/CLOSEOUT OF URANIUM MINES

7.3.1. Planning considerations

In addition to the information given in subsection 7.1, the final plan for the decommissioning/closeout of uranium mines should include:

1. A reassessment of the design criteria for decommissioning/closeout of the mine.
2. The time sequence for dismantling and removing equipment, support systems, ventilation ducts and other surface and subsurface structures associated with the mine.
3. A list of the remedial actions required to ensure the long term stability of the mine in order to control surface subsidence in underground mines or wall stability in open pit mines.
4. A decision on the future use of the mine, if any; it could be used for the disposal of mill tailings, contaminated residues, demolition wastes, etc., or be left empty.
5. Identification of those mine openings that are to be sealed and a plan for achieving their closure.
6. Consideration of the reactivity of residual rock in exposed surfaces of the mine and an assessment of its possible impact on groundwater.
7. In the case of mines that are to be flooded, a description of the measures that will have to be taken in order to avoid unacceptable groundwater contamination.
8. The post-sealing monitoring plan.

7.3.2. Technical considerations

7.3.2.1. Underground mines

For underground mines, two closeout options are possible: leave the mine empty; or fill it with tailings, heap leach residues, contaminated demolition material, inactive waste rock or other suitable material, taking into account the mine stability, hydrological and geological considerations and the distribution of shafts and galleries: temporary dewatering/seepage control systems may be required.

If a mine is located within a groundwater region, it will eventually flood because eternal pumping is neither possible nor desirable. Therefore, rather than being an option mine flooding is often a fact requiring technical consideration.

For all options, entrances to primary shafts, declines, adits, exits and other openings to the mine should be filled with inactive rock or solid non-shrinking concrete keyed into solid rock, where possible, to prevent intrusion by humans. Small holes may be left to permit access by animals such as bats. If long term isolation from
the biosphere can be demonstrated, then release of the mine without radiological restrictions may be allowed. All closeout options should be evaluated for their effect on controlling further activity release to the environment.

The decommissioning/closeout plan should also ensure the long term stability of closed out mines to prevent surface subsidence and to reduce seepage to acceptable levels. The subsidence resulting from the collapse of abandoned mine workings can result in physical hazards to humans living in the area and could also lead to the creation of new pathways for the migration of pollutants from the mine.

7.3.2.2. Open pit mines

The options available for decommissioning/closeout of an open pit mine depend on the reactivity of the wall rock, the stability of the walls in the long term, safety considerations, aesthetic values, possible future land uses and existing drainage patterns. The range of options for the decommissioning/closeout of open pit mines include leaving the pit as excavated at the end of operation; reworking the benches to achieve flatter slopes; flooding the pit; and filling the pit with mill/mine residues. These options and the technical considerations applicable to them are discussed in the following subsections.

7.3.2.2.1. Leaving the pit as excavated at the end of operation

In this option, the pit is left as it was on completion of operation. If necessary, slopes would be smoothed out and the exposed surfaces covered with appropriate materials to decrease gamma radiation, radon emanation and the dispersion of other contaminants. The technical requirement that open pits remain stable during mining could, in some instances, mean that the pit walls will be stable in the long term. This option is particularly suitable in arid areas.

7.3.2.2.2. Reworking the benches to achieve flatter slopes

Closeout studies may indicate that wall slopes considered safe during operation may not be safe in the long term owing to factors such as a combination of joint orientation, clay filled joints and saturation of walls. Safety considerations would therefore dictate that the benches be reworked to flatten the slopes, both to reduce the likelihood of wall failure and to minimize the chances of accidents occurring under future land use.

7.3.2.2.3. Flooding the pit

If the water table is close to the pre-mining surface or if the surface drainage flows to or through the open pit, it may be difficult to keep the pit dry. Provided
that the hydrological characteristics are suitable, it may be advantageous to allow the pit to fill with water, with the provision of overflow facilities, if necessary. The water body so formed would be in dynamic equilibrium with the groundwater level, precipitation, inflow, outflow and evaporation.

This approach may allow for unrestricted release of the mine. As well as minimizing the potential for intrusion and assisting in reducing the rate of radon exhalation by covering rock surfaces with water, a water body that is flushed regularly can have the advantage of maintaining the pH at a level which is less conducive to the mobilization of some trace elements. However, an analysis should be performed to assess the potential for transporting contaminants to the environment.

Evaluation of the long term impact of the open pit water on the surrounding groundwater is important, since the water contained in aquifers that connect with the pit may have differing qualities.

7.3.2.2.4. Filling the pit with mill/mine residues

The open pit could be filled with mill tailings, clean waste rock, low grade ore, heap leach waste residues or decommissioning waste equipment/materials. This reduces the need for new disposal facilities and the volume of waste remaining on the surface. Dewatering and drainage systems may be required to consolidate the disposed residues. The filled-in pit should be covered with clean material and contoured according to the requirements of the intended land use.

One procedure for improving the logistics of handling debris from an open pit mine is sequential stripping during mining. An area of the site is stripped and the waste rock stored while the ore is mined. Then another portion is stripped, its waste rock being used to backfill the first pit strip. Thus, less debris is left at the end of mining. Essentially, reclamation is taking place concurrent with the mining operation. This procedure is possible if the geometry of the ore body lends itself to this approach.

Appropriate engineering controls should be provided so that contaminants will not diffuse into the environment at an unacceptable rate. The technical options relating to retention and cover barriers for tailings and mining debris (subsections 7.4 and 7.5, respectively) should be taken into account in closing out a waste filled pit.

In the case of a pit filled with mining debris, water may fill the pores of coarse, porous rock. This water will respond to inflows, outflows and changes in the groundwater levels in a manner similar to a water body. However, the overlying waste materials will reduce the impact of evaporation on the water balance for the open pit.

The significance of this is highly site specific and dependent also on the effectiveness of a cover in controlling infiltration and inflows by runoff from the surrounding catchments.
7.4. DECOMMISSIONING/CLOSEOUT OF TAILINGS IMPOUNDMENTS

7.4.1. Planning considerations

In planning the closeout of a tailings pile, the planners must have a good understanding of the hazards involved and the means of controlling such hazards [3]. Although the radioactivity and some toxic chemical constituents in mill tailings are natural in origin, after mining and milling they are left in a chemical and physical form that could increase their mobility in the environment. Consequently, it is more likely that some of these pollutants will be dispersed into the environment, causing unacceptable effects.

Because of the presence of residual long lived radionuclides, the residues from the mining and milling of radioactive ores will remain radioactive for several hundred thousand years. The specific activity is typically low in comparison to that of some waste from other parts of the nuclear fuel cycle, although tailings that result from the milling of high grade ores can represent a radiological hazard comparable to that of low level radioactive waste. While tailings and residues from the mining and milling of radioactive ores can generally be categorized as very low level waste, the quantity of material requiring disposal is much larger than the quantity of waste from other parts of the nuclear fuel cycle.

As part of the planning for the decommissioning/closeout of mill tailings impoundments, an assessment will have to be made to determine if the present impoundment and site will safely retain the tailings and the contained radioactive and chemically toxic pollutants for the length of time required by regulatory criteria. If the safety assessment shows that the present impoundment would not be safe for the required length of time, remedial actions would have to be undertaken to bring it up to standard.

If the site is unsatisfactory and the impoundment cannot be improved to compensate for site inadequacies, it may be necessary to relocate the tailings on-site or to a new site. Relocation may be considered if:

1. There are excessive radiological exposures to nearby residents (alternatively, people could be relocated if that was socially acceptable and cost effective)
2. The location of the tailings requires impractical or excessively costly flood protection measures
3. There are unsuitable geological or geomorphological site characteristics, e.g. if the subsurface soils are potentially liquefiable in an earthquake
4. There is an inability to achieve adequate groundwater protection at the site.

The relocation of tailings is very expensive and time consuming when compared with in situ stabilization and often introduces new environmental concerns. If the new facility is away from the mine/mill site, an environmental impact assessment would be required to confirm the safety of the new site and the transportation of large
volumes of contaminated material, possibly for long distances over public roads. Relocation should only be considered in cases where a comprehensive health/environmental and socioeconomic analysis indicates significant net benefit in comparison to in situ options.

The need to relocate may be more common for older mine/mill facilities, where the siting and design of tailings impoundments were not as well regulated as they are currently. A process for selecting an alternative site is described in subsection 6.3.

True decommissioning of tailings impoundments is seldom practicable and is limited to cases where intrusion or removal of materials by humans is highly unlikely, even in the very long term. Examples where decommissioning might be possible include disposal of tailings into an underground mine, a deep natural water body, or an open pit covered with water or a very thick intrusion resistant cover. For the above ground piles, the impoundment would be constructed and closed out according to sound engineering practice and regulatory requirements and be kept under institutional control.

In planning for the closeout of tailings impoundments, mining debris piles (subsection 7.5), and heap leach piles (subsection 7.6), the following guidelines should be considered:

(a) Radioactive and non-radioactive contaminants released to the environment during and after closeout should not exceed authorized limits and should be as low as reasonably achievable (ALARA), taking into account economic and social factors
(b) Reliance on long term active institutional controls as a means of adhering to regulatory criteria after closeout is complete should be minimized
(c) Passive barriers, either natural or engineered, should be favoured
(d) Containment systems should be designed so that degradation leads to gradual rather than sudden release of contaminants
(e) Requirements for the maintenance of containment systems should be minimized and options requiring frequent maintenance should not be used.

In addition to the items listed in subsection 7.1, planning for the closeout of tailings impoundments, mining debris piles and heap leach piles may include, as appropriate, the following information:

(i) Plans for the stabilization of tailings impoundments in situ or relocation to another site
(ii) Plans for the control of spillage and dust during transport in the event of relocation
(iii) Methods for the long term control of contaminant releases
(iv) Methods for the control of intrusion and unauthorized removal of tailings
(v) Plans for the control of groundwater contamination
(vi) Plans for the cleanup and release of contaminated areas.
1. Tailings or other contaminated material
2. Top slope cover: a multicomponent system as required to control radon gas escape, to reduce water infiltration and to eliminate erosion
3. Side slope cover or cleanfill dykes: to provide static and dynamic slope stability, to control erosion, to reduce infiltration and to control radon flux
4. Erosion control apron: rock layer to control both erosion of perimeter soil and head cutting of gullies
5. Diversion channel: to divert upgradient runoff
6. Cell foundations: stable, low permeability soils and rock

**FIG. 3. Main components of a closed out uranium mill tailings pile.**

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**FIG. 4. Multilayer cover [38].**

- Vegetation
- 0-30 cm Rock mulch
- 90 cm Growth medium and frost protection
- 30 cm BiobARRIER: cobbles (top choked or filtered)
- 15 cm Drain: clean sand infiltration barrier
- 30 cm Radon barrier: clay/silt

**Note:** Thicknesses are approximate
<table>
<thead>
<tr>
<th>Cover component</th>
<th>Purpose and function</th>
</tr>
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<tbody>
<tr>
<td><strong>(1) Erosion barrier vegetation</strong> <em>(top slopes only)</em></td>
<td>Transpire moisture that enters the soil&lt;br&gt;Reduce infiltration&lt;br&gt;Stabilize soil and reduce erosion&lt;br&gt;Minimize impact of rainsplash</td>
</tr>
<tr>
<td><strong>(2) Erosion barrier small diameter rock layer above topsoil on pea gravel/soil mulch</strong> <em>(top slopes only)</em></td>
<td>Provide additional protection against soil erosion, used in conjunction with vegetation&lt;br&gt;Reduce evaporation rates within the underlying soil layer in drier environments — preclude drying of the radon barrier</td>
</tr>
<tr>
<td><strong>(3) Rooting medium</strong> <em>(top slopes only)</em></td>
<td>Provide rooting medium for vegetation&lt;br&gt;Store water for plant growth&lt;br&gt;Protect the underlying biointrusion layer from surface exposure&lt;br&gt;Provide frost protection</td>
</tr>
<tr>
<td><strong>(4) Frost protection</strong> <em>(random fill)</em> <em>(top and side slopes)</em></td>
<td>Protect the underlying layers from the effects of frost heave and frost penetration&lt;br&gt;Preserve the physical properties of the underlying layers</td>
</tr>
<tr>
<td><strong>(5) Choked rock filter</strong> <em>(layer of pea gravel overlying a layer of coarse aggregate)</em> <em>(top and side slopes)</em></td>
<td>Prevent piping of soil into erosion/biointrusion barrier&lt;br&gt;Drain infiltration as rapidly as possible to retard root growth</td>
</tr>
<tr>
<td><strong>(6) Erosion/biointrusion layer</strong> <em>(500–1000 mm of cobbles with a low coefficient of uniformity to prevent biointrusion)</em> <em>(top and side slopes)</em></td>
<td>Drain infiltration as rapidly as possible to retard root growth&lt;br&gt;Impede burrowing animals&lt;br&gt;Act as capillary break at the bottom of the layer to prevent upward movement of water and downward unsaturated flow (enhances the moisture storage capacity)&lt;br&gt;Control top slope erosion if vegetation and top-soil are eroded away</td>
</tr>
<tr>
<td><strong>(7) High permeability drain</strong> <em>(150–300 mm layer of pea gravel overlying clean sand)</em></td>
<td>Drain water laterally off the pile to limit infiltration&lt;br&gt;Protect the underlying liner system from displacement and rock penetration</td>
</tr>
<tr>
<td><strong>(8) Infiltration barrier/Claymax® liner system</strong> <em>(top slopes only)</em> or high percentage bentonite mix <em>(with silt or sand)</em></td>
<td>Intercept moisture&lt;br&gt;Control infiltration&lt;br&gt;Inhibit infiltration while mature vegetation community is establishing or after severe disturbance of the vegetation</td>
</tr>
<tr>
<td><strong>(9) Radon barrier</strong> <em>(clay/silt)</em> <em>(top and side slopes)</em></td>
<td>Inhibit radon emanation&lt;br&gt;Limit infiltration</td>
</tr>
</tbody>
</table>
7.4.2. Technical considerations

The major technical features associated with tailings impoundments include covers, vegetation, perimeter dams, dykes or embankments, basal features, water diversion and control features and foundations [3, 38]. For the closeout of an impoundment, these features must meet regulatory standards, or be brought up to these standards by remedial work. These features, which apply to in situ or relocated impoundments, are discussed briefly in the following subsections (see Fig. 3).

7.4.2.1. Covers

In most cases, tailings in an impoundment may have to be covered to limit radon emanation, moisture infiltration, gamma radiation, oxidation, intrusion by humans, plants and animals, and erosion.

Cover materials can be classified broadly as natural (soil, rock, clay, vegetation, etc.), artificial (plastics, asphalt, soil/concrete mixtures, etc.) and water [3]. The materials may be used in different combinations, configurations and thicknesses. A combination of two or more materials may improve cover performance and provide added resistance against detrimental processes such as erosion and biointrusion. However, in some cases, for example, where long term settlements are to be expected, a complex cover design may have disadvantages because of its vulnerability.

Figure 4 [38] shows an example of a multilayer cover. To select components appropriate to a specific impoundment, refer to Table I [38], which lists the purpose and function of various cover components.

The long term performance of synthetic materials is questionable, since they may degrade and fail to function as required. In addition, they may be too expensive.

A water cover will prevent radon emanation, erosion and intrusion. Where tailings are susceptible to acid production, water may be a desirable approach for excluding oxygen. Issues such as groundwater contamination and retaining dam stability should be included in the assessment of water covers [40]. If the water level is controlled by an artificial dam, long term institutional control may be required to ensure that the integrity of this structure is maintained. Should the dam fail, the water cover, and possibly a portion of the tailings, would be lost. In addition to the significant hazards associated with the dam failure itself, problems could arise with radon emanation, dust, erosion and migration of tailings.

One disadvantage of a water cover is that it creates hydraulic pressure on the pore water system, possibly causing contaminants to move into the groundwater or surface water systems.

An alternative is to place the tailings in a natural water body, both during production or as a relocation option, if required. Although this is a promising tech-
nology, there may be considerable social pressures against ‘sacrificing’ a lake for such waste disposal.

7.4.2.2. Vegetation

Once the graded pile has been covered with a layer of good soil, if available, it may be revegetated to assist in the control of dust and erosion, to improve slope stability, to reduce rainwater runoff, to enhance the aesthetics of the site, and to improve the productive use of the pile, e.g. trees.

The final vegetation should be self-sustaining and capable of adapting to the site conditions. It should not have root systems that could penetrate through and damage the cover. Initially, the vegetation may comprise exotic species to provide rapid protection. However, species indigenous to the area should be used to achieve long term protection. Exotic species should not be used as a final vegetative cover without the approval of the regulatory authority. Annex IV is a checklist for the revegetation of closed out tailings.

Revegetation may be the preferable choice in many cases. However, it also has some disadvantages such as root penetration into the cover and possible loss of the erosion protection potential based on vegetation in the event of climate changes. Other options, e.g. riprap, may avoid these problems. Decisions should be made on a site specific basis.

7.4.2.3. Perimeter dams, dykes or embankments

Selection of the layout for a perimeter dyke/dam depends on the site topography, e.g., a valley or plain; the optimum depth of excavation if the tailings are relocated; the existing perimeter dyke construction if stabilized on-site; the availability and properties of the construction and erosion control materials; and the geometric configurations required for slope stability.

Retaining walls can be constructed of rock, soil, concrete, etc. Standard and widely available slope stability programmes can be used to determine the resistance of the dam slope to static and seismic forces. The various designs of impoundments that use dykes or dams are discussed in detail in Ref. [3].

7.4.2.4. Basal features

Liners of relatively low permeability to seepage, geochemical barriers and drains may be needed to prevent leakage into the foundations and migration of contaminants into the groundwater. If a liner is to be used, consideration must be given to its durability and its permeability relative to those of the cover in order to prevent buildup of a hydraulic head. Synthetic liners are not recommended as a long term protection measure.
A geochemical barrier may be placed before relocation of the tailings if an alteration in the quantity/quality of the leachate from the tailings is needed to achieve the groundwater protection requirements.

7.4.2.5. Water diversion and control features

Ditches, canals or dykes may be placed around impoundments to protect them from upgradient runoff. Such facilities can be lined to control erosion. If rock is used for the lining, its quality should be adequate to resist degradation for the design life of the facility. Diversion facilities, where required, should be located such that potential erosion during the facility design life will not affect the integrity or stability of the closed out tailings.

The geometry and gradients of diversion facilities should be selected to preclude settling, clogging or the development of conditions that may impede flow in the ditch during critical situations such as a design precipitation event. In particular, the long term surveillance and monitoring plan should provide for the periodic removal of excess vegetation that may grow in ditches. In addition, where necessary, plans should be made to control the results of fauna, e.g. beaver, activity.

7.4.2.6. Foundations

Impoundment designs should accommodate the particular requirements of the soils and rocks under it as well as those in the immediate vicinity. The factors to be considered include the impact of foundation soils and rocks on perimeter dyke slope stability; settlement of the foundation in response to placement of the tailings or changes to the impoundment geometry during reclamation; instability of the foundation soils as a result of liquefaction due to a design earthquake; and geomorphic alteration of the adjacent soils and rocks, particularly by erosion, that could affect the stability and integrity of the closed out tailings.

7.5. DECOMMISSIONING/CLOSEOUT OF MINING DEBRIS PILES

7.5.1. Planning considerations

Mining debris is waste rock or soil with practically no (or low) uranium grade, which cannot be milled economically. This debris can be utilized in a number of ways, but its mineralogy, radioactivity and chemical reactivity should be assessed before a decision is taken to use it as a source of uranium that can be recovered by heap leaching; to refill open pit or underground mines; or to construct dams, dykes, embankments, water diversion ditches, covers for tailings piles, roads and other similar projects on the mine site [4].
Piles of mining debris could be decommissioned if requirements similar to those mentioned in subsection 7.4.1 for mill tailings are met, e.g. disposal in an underground mine. When there is no other closeout alternative to placing mining debris in piles constructed above ground, these facilities should be constructed and closed out according to sound engineering practices, and be located such that the impact on the environment is minimized and the mechanical stability ensured. The information in the last two paragraphs of subsection 7.4.1 also applies to mining debris piles.

The objectives for decommissioning/closeout are long term stability of the mining debris piles; control of the infiltration of precipitation into the pile and of the movement of physical, chemical and radiological contamination to the environment; and, if required, minimization of the visual impact of piles by integrating them into the landscape.

7.5.2. Technical considerations

The technical design and work needed to decommission/close out mining debris piles will vary considerably from site to site because of site specific factors such as the climate; the location; the amounts and characteristics of the waste material; and the requirements, e.g. land use, of the regulatory authority.

In planning the decommissioning/closeout of mining debris piles, the following technical requirements must be given consideration: covers, vegetation, water diversion and control features, and use of mining debris as a construction material. Some of the techniques used could be similar to those employed for tailings impoundments (subsection 7.4).

7.5.2.1. Covers

At many mines, large volumes of inactive soil and rock form part of the mining debris. Where practical, this material should be stored separately and used later, if required, to form a cover over the mining debris pile as part of a sealing and revegetation programme. Borrow pits for these materials may then be either unnecessary or at least minimized.

When soil is used as part of the cover and placed directly over open graded rockfill, a filter should be placed between the two materials to prevent the soil from being washed down into the interstices between the rock particles. Crushed weathered rock may be suitable for this purpose. Crushing of selected hard mining debris can also produce good filters, but usually at a higher cost. Careful control of the grading of the filter material is important.
7.5.2.2. Vegetation

See subsection 7.4.2.2.

7.5.2.3. Water diversion and control features

See subsection 7.4.2.5.

7.5.2.4. Use of mining debris as a construction material

Mining debris is a valuable construction material on a mine site and should be used, where possible, in preference to material from outside the project area in order to minimize the excavation of additional borrow areas. The suitability of mining debris as a construction material should be based on its general engineering properties and on its mineralogy, radioactivity and chemical reactivity so that it does not become a source of unacceptable contamination.

If suitable, mining debris can be used for construction of embankments, water retention ponds and tailings dams as impervious core material, filters and riprap; as a cover over a tailings impoundment or mining debris piles; for construction of roads, drainage or diversion structures, and drainage channels on rehabilitated areas; and as general fill in the project area or backfill for underground and open pit mines.

Mining debris should not be used as a construction material outside the project area unless approved by the regulatory authority. The requests should indicate the structure and quantity of the material to be used, the limits to contaminant content and the radioactivity.

In principle, unprocessed ore stockpiles could be disposed of along with mining debris or heap leach residues. However, if the mill is still in operation or milling facilities are available elsewhere, the option of processing the stockpiled ore is available.

7.6. DECOMMISSIONING/CLOSEOUT OF HEAP LEACH PILES

Heap leach piles consist of low grade ore that has been partially crushed and leached by applying a chemical lixiviant to remove the uranium.

The objectives for the decommissioning/closeout of heap leach piles are comparable to those for mining debris piles, namely, long term stability of the mining debris piles; control of the infiltration of precipitation into the pile and of the movement of physical, chemical and radiological contamination to the environment; and, if required, minimization of the visual impact of piles by integrating them into the landscape.
In planning the future management of a heap leach pile, two alternatives are available:

(1) Decommissioning the pile by relocating it for disposal at another site such as a tailings impoundment; this approach may be attractive if heap leach piles are small or numerous.

(2) Closing out the pile in situ.

During the closeout of piles, the leaching solution may be removed by flushing with water or a neutralizing solution. The pile can then be considered similar to mining debris and the options discussed in subsection 7.5 adopted.

If the pile still contains high levels of radioactivity or other contaminants, it should be handled in the same way as a tailings pile (subsection 7.4). The information in the last two paragraphs of subsection 7.4.1 also applies to heap leach piles.

7.7. DECOMMISSIONING/CLOSEOUT OF IN SITU LEACHING OPERATIONS

In situ leaching is performed by injecting sulphuric acid or alkaline solutions such as calcium carbonates into an underground ore body to remove the uranium. The solution containing the uranium is then processed to remove the uranium.

The plan for the closeout of in situ leaching operations should ensure that the following technical factors are included or given serious consideration:

(1) All the relevant regulatory and environmental requirements should be met
(2) The possibilities of removing the leaching solution by flushing with water or a neutralizing solution should be evaluated
(3) The means of controlling further leaching of the ore body and contamination of the groundwater should be evaluated
(4) Restoration of the adjacent groundwater system to an acceptable state should be considered.

Decisions on the implementation of these options should be based on site specific assessment of the prevailing risks and the benefits that can be obtained. When flushing the closed out ore body with water or a neutralizing agent to render the leaching solution harmless, the resulting liquid waste can be handled in the ways described in subsection 7.2.2.4.

To re-establish acceptable hydrological conditions, it may be beneficial, if technically feasible, to seal migration pathways such as mine entrances and boreholes.
7.8. CLEANUP OF VICINITY PROPERTIES

The properties near uranium mines/mills and mill tailings waste facilities may become contaminated by wind-blown or water-borne contamination or by tailings/mining debris that was intentionally removed from the mill site and used for fill or for the construction of dwellings.

For example, in Grand Junction, Colorado, USA, over 4000 private properties were built on or constructed of tailings [41]. Other countries have developed similar problems when public works projects (e.g. roads and bridges) were constructed using tailings sands and homes built of ore grade rock from nearby uranium mines or on tailings. In some areas, the cleanup effort is enormous and can be as great as that needed to decommission/close out facilities from which the contaminated materials were obtained.

Risks to occupants or users of contaminated properties vary widely because of the range of contamination levels involved and the physical placement on or in the property. Therefore, every property containing contamination should be evaluated to ascertain the need for and extent of cleanup. Early identification of contaminated properties is important, since the unsuspecting public may be at risk from gamma radiation or radon daughter inhalation.

Cleanup of such properties should be undertaken in accordance with all regulatory requirements. A plan for the cleanup of vicinity properties should include:

1. A radiometric survey to determine which land areas, water systems, buildings and materials are contaminated, including the activity levels and the depth of contamination
2. Determination of the volumes of contaminated material for long term storage or disposal
3. Identification of the materials suitable for unrestricted release before and after decontamination
4. A programme for the radiological protection of workers and the public during the cleanup activities
5. The means of controlling future unauthorized removal of tailings/mining debris and the spreading of wind-blown or water-borne contamination from the mine/mill site to vicinity properties.

Vicinity properties are generally cleaned up by removal of contaminated soils and materials to an approved location. If approved by the regulatory authority, contaminated soils may also be covered rather than removed. Building materials that are not heavily or deeply contaminated may be decontaminated by washing.
7.9. RESTORATION OF SITE

Once mine/mill facilities have been decommissioned/closed out, the area should be restored according to the requirements of the intended land use.

A site restoration plan may include the filling of excavated areas with acceptable fill to contour the site according to the requirements of the intended land use; the spreading of topsoil on the reshaped areas to serve as support for vegetation; and the re-establishment of indigenous vegetation to stabilize the site and integrate it into the landscape.

7.10. REMEDIATION OF GROUNDWATER

If groundwater has been contaminated by the operation of a uranium mine/mill, it may be necessary to restore the groundwater quality to limits established by the regulatory authority. Groundwater restoration can be done by extracting the contaminated groundwater for treatment, evaporation or discharge, and by increasing the natural flushing rate (subsection 8.10).

Groundwater restoration may not be required by the regulatory authority, or be appropriate, if one or more of the following conditions apply:

- The groundwater quality is acceptable or is expected to return to acceptable levels as a result of decommissioning/closeout and natural flushing; institutional controls may have to be imposed until the water quality becomes acceptable
- A pathway/risk analysis indicates that the health and environmental effects are acceptable
- There is no present or future need for the groundwater
- The groundwater treatment is not technically or economically practicable using conventional water treatment procedures.

7.11. IMPROVEMENT IN THE DECOMMISSIONING/CLOSEOUT PLAN/DESIGN

7.11.1. General technical planning considerations

The technical aspects of a decommissioning/closeout plan must adhere to the requirements of the relevant laws, regulations and codes, and achieve the objectives
for short and long term performance of all aspects of the approved plan. An essential feature of any design is that it should be realistic, practicable and economical.

Any proposed facility design should include provisions to resist, over the long term, the effects of site specific natural phenomena such as earthquakes, floods and severe storms, as well as adequate provision to protect human health and the environment.

The designs and other technical aspects of the plan should be evaluated in the safety assessment to demonstrate that they will meet the proposed criteria. In some cases, planning a phased approach to decommissioning/closeout may be appropriate if:

1. Suitable standards are not available
2. Facilities were to be reopened and reused for mining or other purposes
3. Uncertainty exists about the availability of adequate funds to complete the projected work
4. Uncertainty exists about critical technical actions and their impact on final conditions, e.g. the rate of dewatering of a tailings impoundment and the resulting magnitude and distribution of consolidation settlement.

In the latter case, the designer could use the observational method [42, 43], which consists of compiling a reclamation design for likely conditions, and alternative corrective action designs for anticipated deviations. The response of the facility to the implementation of the plan for likely conditions is then observed. If the response differs from the predicted conditions, then one or more of the alternative decommissioning/closeout plans is implemented.

For example, it may not be feasible or economic to characterize every component of the mill building. For conservatism, the decommissioning plan may postulate high contamination on each component as the likely condition. During the actual demolition, the contamination level of each part may be measured, and if this level is less than a predetermined amount, the part may be placed in a less restrictive disposal cell, or even released for unrestricted use. Such an approach is good practice and in accord with a waste minimization approach that should always be an objective of a decommissioning/closeout design.

7.11.2. Effective methods for improving the plan/design

In developing and assessing the decommissioning/closeout plan or design, Member States may find that the plan or design can be improved or made more cost effective in the following ways: utilization of available resources; consideration of alternative means of controlling long term impacts; and use of features that improve the longevity of the facilities.
7.11.2.1. Utilization of available resources

The plans and designs for decommissioning/closeout of mines, mills, tailings impoundments, etc. should ensure that available resources are used as far as is practicable and environmentally safe. Examples include:

1. Use of an available open pit (instead of building a new impoundment) for the disposal of mill tailings, provided that the pit is suitable
2. Placing of debris from the demolition of mill buildings into the soft slimes of the central part of a tailings impoundment
3. Use of mining debris to build erosion protection covers over tailings, dams/dykes for tailings, or road beds on-site.

7.11.2.2. Consideration of alternative means of controlling long term impacts

Reliance on mechanisms involving ongoing human intervention, e.g. effluent treatment systems, to control the long term impacts from a decommissioned/closed out mine/mill complex should be minimized. However, passive controls such as land use control may be acceptable. Should a licensee propose a plan that requires long term active or passive institutional controls, the regulatory authority may require that the licensee considers the feasibility of alternative solutions to avoid the need for these controls.

This evaluation should compare the nature and cost of alternative controls and the long term capability of the institutions concerned to maintain the proposed controls.

7.11.2.3. Use of features that improve longevity

Member States can, with reasonable confidence, assume that above ground tailings impoundments built with the best available design and technology can last several hundred and even a few thousand years. However, the potential radiological and toxic chemical hazards of the waste will last much longer. Except for underground impoundments, it is not likely that Member States will be able to show clearly that containment structures can last for these much longer times. Therefore, to ensure that the containment structures last as long as possible beyond their design life, they should, where possible, include:

1. Use of natural materials as much as possible
2. A backup of man-made components, which cannot be avoided, with natural materials, whenever possible [44]
3. Emulation of natural topographical and geological forms
4. A design for extreme events, such as probable maximum precipitation and flooding, or maximum credible earthquake
(5) Provision of redundant safety features
(6) Opportunities for a synergistic design in which components work together to a mutually desired performance objective
(7) Provision for inevitable and continuous natural processes (e.g. the growth of vegetation [45]) when these are demonstrated to be favourable
(8) Use of markers, signs and other passive features to denote the site.

A more detailed treatment of the longevity question is developed in Annex V.

8. IMPLEMENTATION OF THE DECOMMISSIONING/CLOSEOUT PLAN

In this section, the general strategy required to implement a comprehensive plan for the decommissioning/closeout of a mine/mill complex is reviewed. Then the factors relevant to implementing the plans for each of the components of the complex, e.g. buildings, mines, mills and impoundments, are discussed.

8.1. GENERAL

While most decommissioning/closeout work can only be implemented after production has ceased, some progressive cleanup or rehabilitation can normally be undertaken during the operating life of a mine/mill. This will assist in minimizing the radiological and environmental impacts during the operating phase, and could lead to the development of applicable site specific solutions, for example, in erosion control or revegetation. As well as providing the site specific data and baseline information necessary for long term decommissioning/closeout planning, progressive rehabilitation usually results in lower costs and in some cases can be used by the operator to recover funds from any rehabilitation bond requirement.

Once the final decommissioning/closeout plan has been approved by the national and regional regulatory authorities and the relevant regulations and requirements have been defined, implementation of the plan can commence.

To ensure that all activities in the plan are implemented and carried out efficiently, the implementing organization should:

(1) Analyse site characterization data from the original site licensing documents, literature, field collection activities, contamination monitoring, borehole sampling, etc.
(2) Develop a detailed implementation plan that complies with all the regulatory requirements related to decommissioning/closeout activities, is based on the site characterization data, the work which must be done, the available technology and other factors, and includes a timetable and sequence of events.

(3) Develop the detailed engineering designs and subprogrammes, e.g. radiation protection, safety, quality assurance, monitoring, security, access control, etc. required to achieve the project's goals and standards within budget and on time.

(4) Carry out decommissioning/closeout activities such as contamination cleanup, demolition, construction, waste disposal and remedial actions in accordance with the applicable regulatory, health, safety and quality assurance requirements.

(5) Develop a surveillance/monitoring plan to assess the long term success of the decommissioning/closeout activities.

(6) Ensure that complete records are kept of all the activities.

The work plan, which should be flexible enough to permit the adoption of new methods and technologies, should also define the responsibilities and functions of the various parties both during and after decommissioning.

While many decommissioning/closeout activities are similar to conventional civil and mechanical engineering construction and demolition, the demands of radiological health and safety and worker protection impose additional considerations. Also, where plans are designed to last for very long periods, higher levels of construction oversight and quality control and assurance are required.

Depending on the national regulatory requirements and contamination levels, exit control facilities and procedures should be established to ensure that personnel and equipment leaving the site are monitored for radioactivity and decontaminated, if required, to acceptable levels. Equipment being removed from the site should be decontaminated to levels approved for either restricted or unrestricted release.

Decommissioning/closeout activities at mines/mills and waste management facilities may result in considerable volumes of contaminated water. The sources include infiltration water in excavations, precipitation runoff from contaminated areas, water from washing and decontamination facilities for personnel and equipment, and existing water at the facility.

In arid climates, evaporation of contaminated water may be feasible. Spray evaporation could be used to augment natural evaporation, taking into consideration the prevailing air quality standards. In wet climates, facilities may have to be provided to treat the water to acceptable levels before release. In some locations, it may be feasible to dilute and disperse waste water, utilizing natural streams. In disposing of waste water in this manner, applicable water quality standards should be met (see subsection 7.2.2.4).

Professional staff who monitor and oversee work programmes should have appropriate expertise and experience. For example, if high quality rock is required
for an erosion barrier, a qualified geologist should be present on-site to observe and consult on the development of the quarry and the provision of rock of a specified quality.

Where possible, personnel normally employed during mine/mill operation should be included in the decommissioning/closeout team, since they have a good knowledge of the plant and of what has taken place in the past. Use of mine/mill personnel should provide cost and efficiency advantages.

The purpose of the following subsections is to provide practical information related to the implementation of specific parts of the decommissioning/closeout plan and, as appropriate, to reiterate briefly the major technical factors that need to be taken into account.

8.2. DECOMMISSIONING OF MINE/MILL BUILDINGS AND FACILITIES

The implementing organization must procure the decontamination, cutting and demolition methods and equipment that are required to decommission the equipment, structures and buildings, as well as the teams to carry out the plans.

The equipment and techniques [14-18] that are widely used during the maintenance and decommissioning of all types of nuclear facility can also be used in the decommissioning of mine/mill facilities. However, since mine/mill facilities tend to produce more dust than most other nuclear plants, additional dust controls above those typically used should be considered. Loose contamination should be removed from building surfaces, equipment, ducts, tanks, etc. before demolition.

Interior structures, machinery and equipment that do not compromise the structural integrity of the building should be decontaminated as required and relocated to controlled storage areas before the building is demolished.

Pipes and ducts should be cut into convenient sizes to facilitate handling and sent for storage if they are to be recycled, or for disposal in tailings impoundments, mines or other acceptable locations. Tanks and vessels may have to be cut into pieces and flattened to facilitate ease of handling and transport. Some metal, concrete and masonry components may require cutting or, in some cases, more vigorous demolition methods such as explosives.

Cutting and demolition methods should be carefully chosen to control the spread of dust and to minimize the airborne and water-borne release of contaminants. Adequate dust control measures should be taken during all demolition work. Dust control can be achieved by many methods, e.g. spraying with a water mist, temporary enclosures during dismantling, and vacuuming contamination already present on floors.

Unless salvage is contemplated, pipes, ducts and tanks only need to be emptied of their contents to the extent required in order to permit removal and dismantling
and to minimize the dispersal of contaminated dust or liquids during dismantling, handling and disposal.

After removal or decontamination to acceptable levels of all the equipment, buildings and structures, the mine/mill site may be graded and revegetated to blend in with the surrounding environment and released for unrestricted use.

8.3. DECOMMISSIONING/CLOSEOUT OF URANIUM MINES

In addition to the issues presented in subsection 7.3, the implementing organization should give special consideration to the following items during the decommissioning/closeout of uranium mines.

Materials such as petroleum products or explosives, which could become significant contaminants in groundwater, should be removed from the mine and reused/recycled if possible, or disposed of according to the requirements of the regulatory body.

Once the mechanical and hydraulic integrity of an open pit mine have been assured and approvals obtained, the pit could be used as an impoundment for tailings and mining debris. The waste should be spread and compacted and covered with a suitable cap so as to limit the migration of contaminants to the environment.

Special attention should be paid to the mine water before, during and after decommissioning/closeout. When concentrations of radionuclides and other contaminants in the water are higher than those acceptable for discharge to the environment, mine water may have to be treated to achieve the desired levels.

If necessary, tunnels and shafts in underground mines can be filled with concrete or any suitable mining debris to prevent surface subsidence. If tailings are used, the coarser fraction is more suitable for this purpose; however, slimes remain, which are much harder to stabilize. All openings into an underground mine that could permit intrusion by humans should be sealed appropriately.

8.4. DECOMMISSIONING/CLOSEOUT OF TAILINGS IMPOUNDMENTS

The two main options for decommissioning/closing out of tailings piles are stabilization of the tailings in place with covers, and relocation of the tailings and rehabilitation of the original area.

If earth covers are specified, the construction requirements and schedules may require dewatering and consolidation of the tailings that are to be closed out in place. If consolidation is slow or the magnitude of consolidation settlement is large, the rate of construction and placement of the fill and cover may have to be restricted in order to avoid instability or deformation induced cover cracking. Consolidation can be expedited with drains [38].
8.4.1. Stabilization in place with covers

The alternatives for covering tailings, either stabilized in place or relocated, are described in subsection 7.4.2. The factors to be considered during the placement of the covers are discussed below.

Natural covers consisting of clay, soil, sand, rock or other earthen materials may be placed in engineered layers (Fig. 4). Placement of these covers requires careful attention to the moisture content, compaction and thickness. When multiple layers are placed, care should be taken to limit the disturbance of each in-place layer as the new layer is placed. Depending on the size of the disposal area, different parts of the final cell may have to be constructed at different times. In this case, care should be taken to join the multiple layers as they meet in the different subareas to ensure that the edge effects are minimized.

Covers may be constructed of man-made materials such as asphalt or concrete in conjunction with natural materials. The primary concern with these materials is their lack of longevity compared with natural materials. The most difficult implementation problem with their use is crack prevention.

When using water as a cover, care should be taken that migration of contaminants into the water is kept to acceptable levels. Other issues which may require addressing are exchange of tailings pore water with the local groundwater, the long term stability of impoundment dams and the long term integrity of the water cover.

8.4.2. Relocation of tailings to an alternative site

In implementing the relocation of tailings to a new site (subsection 6.3), the following disposal alternatives can be considered [3]: placement in an underground mine, placement in an open pit mine or a specially dug pit, or placement in a ring dyke or a valley dam impoundment.

8.4.2.1. Placement in an underground mine

Tailings can be transported into stable accessible tunnels and shafts of a mine by 'reverse mining' techniques or by hydraulic pumping of the slurry through boreholes. Owing to the 'swelling' of mined ore and the addition of chemicals during milling, a mine may not be able to take back all the tailings that result from the milling of the ore removed from the mine. Although placement of cycloned (coarse) tailings has been practised in many mines as a mining technique during operation, no cases are known of placing tailings underground for the purpose of decommissioning. If this method is used, some factors must be addressed, e.g. optimal use of the underground volume, minimization of contaminant migration to the groundwater and worker health and safety.
8.4.2.2. Placement in an open pit mine or a specially dug pit

Where conditions are suitable, it may be possible to return tailings to a mined out pit. The implementing team will have to ensure that the stability of the pit and the vulnerability of the groundwater systems are satisfactory. Although this method has been used in many mills, e.g. the Cameco Rabbit Lake mine in Canada, for placement of milled tailings, there is no record of this method being used for the relocation of already deposited tailings. Placement of tailings into a specially dug pit impoundment is fundamentally the same as placement of tailings into a mined out open pit, and many of the same considerations apply.

8.4.2.3. Placement in a ring dyke or a valley dam impoundment

Movement of tailings to a ring dyke or a valley dam impoundment [3] at an off-site location would require an environmental impact assessment of the new site and the transportation hazards, as well as the transportation of large volumes of contaminated material, possibly for long distances over public roads. If the new impoundment is to be located on-site, the transportation requirements are less restrictive.

8.5. DECOMMISSIONING/CLOSEOUT OF MINING DEBRIS PILES

Since material in these piles may originate from the removal of barren rock and overburden in underground or open pit mines to gain access to the ore body, or be unprocessed low grade uranium bearing rock, the pile is often quite variable in its radioactive, physical and chemical characteristics.

An overall assessment of the characteristics of the mining debris and the options available for managing it (subsection 7.5) should be the basis for implementing the method for managing the mining debris piles. Remedial actions for the mining debris may entail using it for heap leaching, or relocating, reshaping and/or covering piles to meet the long term closeout requirements of the regulatory authority. In most cases, remedial work entails earth moving activities; the requirements for worker health and safety, environmental compliance and quality control during this work are essentially the same as those for the decommissioning/closeout of tailings impoundments. However, the radioactivity of mining debris piles is generally much less, and the remediation requirements may be less restrictive.

8.6. DECOMMISSIONING/CLOSEOUT OF HEAP LEACH PILES

During implementation of the decommissioning/closeout plan, residual fluid in the pores of the heap leach pile may be removed or neutralized by continuous water
washing of the rock using the injection and extraction system originally employed in the leaching process. The addition of neutralizing chemicals to the wash water or on the top of the heap leach piles may be beneficial.

The wash water may require treatment. If the original extraction circuit is available, it can sometimes be modified for this purpose. If not, a special ion exchange or reverse osmosis cleanup plant may be required. The extracted salts should be disposed of with care, since they may contain more concentrated levels of contaminants than were present in the original ore.

In heap leach piles containing a significant amount of sulphides, bacterial oxidation may result in the formation of acid, even after washing and neutralization. In these cases, a neutralizing agent such as limestone (calcium carbonate) could be placed on the pile. If the pile is to be relocated, this agent could be mixed into the pile material.

Once the heap leach pile has been washed and the pore water neutralized, the remaining material is similar to mining debris and can be managed in a similar fashion (subsection 7.5).

8.7. DECOMMISSIONING/CLOSEOUT OF IN SITU LEACHING OPERATIONS

Once in situ leaching of the ore body is complete, the closeout actions focus on two main areas: removal of residual leachate and groundwater restoration.

The residual leachate may be removed by water washing of the ore body to prevent further leaching. If necessary, the groundwater in the vicinity of the ore body can be restored to a planned baseline quality by replacing the liquids in the pores with several pore volumes of water. Groundwater flushing should be directed to the centre of the former leaching area by maintaining a slightly pressurized water curtain at the outside boundary of the old leach field. This prevents migration of contaminants into the surrounding uncontaminated groundwater.

For flushing the in situ leach area with water, the old wells used for injecting the leach solutions during operation can be used. For ore bodies turned to rubble by blasting, underground flooding may be used to flush the leached area. The wash water should be monitored for contamination levels and treated, if required, before reinjection. Treatment methods include ion exchange or reverse osmosis.

At times, it may be necessary actively to prevent the movement of ions of toxic contaminants such as heavy metals. This can be achieved by allowing the ion to form an insoluble complex, thus fixing it in a stabilized form. After completion of remediation, monitoring of the leach facility should be conducted to establish that the cleanup objectives have been met.
8.8. CLEANUP OF VICINITY PROPERTIES

The first step in implementing a remediation programme for contaminated vicinity properties is the identification and characterization of properties containing radioactive material. This can be performed by examination of historical records; monitoring of airborne gamma radiation; detection of gamma radiation from vehicles on all roads in a selected radius from the mine/mill facility; detailed on foot gamma radiation monitoring of properties identified by other methods; and core sampling of properties suspected of having deep contamination.

After a contaminated property has been identified, the owner(s) should be contacted and agreements reached on permission to perform detailed surveys and to carry out remediation, if necessary. The agreements should outline the responsibilities, the timetable for physical work and who pays for what. The agreements should be legally binding to prevent misunderstandings between the owner and the cleanup agent.

Because almost all vicinity property remediation involves physical modification of privately owned structures, rehabilitation of the property after countermeasures have been completed is very important to the property owner. Detailed engineering plans should be developed for each property and agreed to by the owner.

Generally, contaminated properties are cleaned up by the removal of radiologically contaminated materials. Those parts of the affected property that are not removed may be decontaminated or rendered acceptable by other means such as covers, ventilation and washing.

The radiologically or chemically contaminated material removed from the property should be safely stored or disposed of. One common option is to place this waste with the tailings or mining debris.

After remediation, the property should be resurveyed thoroughly to verify that the exposure risks have been reduced to acceptable levels. When all the work has been completed, records documenting the remediation should be filed with the appropriate government agencies. Section 11 presents a discussion of the financial responsibility for this work.

8.9. RESTORATION OF SITE

Once the buildings and facilities in a mine/mill complex have been decommissioned/closed out, residual radiological and chemical contamination on-site should be cleaned up until the contamination levels are below the regulatory release criteria. The area should then be restored to meet the requirements of the intended land use (see also subsection 7.9). This restoration can be accomplished by conventional earthmoving and appropriate revegetation techniques.
In some Member States, a more extensive restoration of mine/mill sites has been attempted. This process involves restoration of the site and its ecosystems to their initial conditions; it requires comprehensive knowledge of the pre-mining ecological baseline conditions of the site.

8.10. REMEDIATION OF GROUNDWATER

Extraction of contaminated groundwater for treatment can be achieved by extraction wells or trenches. Water decontamination systems could include filtration, chemical treatment, ion exchange and reverse osmosis. The regulatory authorities normally set criteria that must be met before the treated groundwater can be released or reinjected into the environment.

The residue wastes (which may be both radioactive and hazardous) from a groundwater decontamination system may be active enough to require disposal along with the tailings or mining debris.

If natural flushing is the appropriate procedure for aquifer restoration, the groundwater cleanup period may be shortened using gradient manipulation to direct the flow, injection wells to increase the flow rate, and limited extraction, treatment and reinjection.

Design of a groundwater cleanup system is seldom able to account for all the details of the natural system to be restored. It is normally impractical to obtain sufficient data to characterize the contaminated aquifer fully and to predict its response to a reasonable cleanup system accurately.

In such cases, the observational method may be used [42]. Use of this method (see also subsection 7.11.1) provides a structured and formal procedure for undertaking groundwater restoration in an economic and efficient way. If the water system does not respond satisfactorily and as predicted to the first extraction and cleanup plan, then a predetermined alternative plan is implemented.

9. RADIATION PROTECTION, HEALTH AND SAFETY PROGRAMMES DURING DECOMMISSIONING/CLOSEOUT ACTIVITIES

Radiation protection, health and safety programmes for the decommissioning/closeout of a mine/mill facility should be designed to protect workers, the nearby public and the environment, all of which are interrelated. These programmes should be based on the same principles that are routinely used to implement similar programmes at other nuclear facilities [17, 46, 47].
Most risks associated with the decommissioning/closeout of uranium mines/mills can be managed safely by careful planning, good design, implementation of radiation protection, safety and health programmes and rigorous worker training. The physical, chemical and radiation hazards identified during site characterization (Section 6) should be used in the development of these programmes.

Since closeout of uranium mining and milling waste often involves significant earthmoving, the implementing organization will have to procure the required equipment and trained operators. The group directly responsible for the work should have experience with heavy earthmoving equipment, good organizational and record keeping abilities and a good record of compliance with health, safety and environmental programmes. Often the required equipment and personnel are available from the mill’s operating resources.

Risks to workers, other than those related to construction safety, stem from exposure to radiological and non-radiological hazards during the dismantling of structures and cleanup of the site. Risks to the public and the environment arise from any of the migration pathways (subsections 5.2.2 and 10.2) which are active at the site under consideration.

To reduce risks to workers, the public and the environment, dust control, air and water sampling, worker radiation monitoring and a traffic control system should be continued until the site is released. The goals and requirements of these programmes should be similar to those applied during operation of the mine/mill. Many procedures used to protect workers in an operating mine/mill are appropriate to decommissioning/closeout.

9.1. DUST CONTROL

Dust control programmes and/or use of respirators may be required to reduce the risks from airborne hazardous particulates. Water sprays and dust control agents, e.g. magnesium chloride, can be used to reduce particulate releases. A balance between the need for dust control and the vehicle traffic requirements should be maintained.

Performing as much dismantling as possible inside closed buildings will help prevent the release of radioactive dust. For badly contaminated equipment, plastic work tents could be used to reduce the spread of contamination during decontamination procedures and dismantling. Residue waters from dust control and decontamination should be managed carefully.

9.2. AIR AND WATER SAMPLING

Continuous air and water sampling for long lived alpha particle and radon daughter concentrations should be done on-site and in vicinity properties during
remedial actions. If thorium is present in significant concentrations, spectrometric alpha analysis may be required to demonstrate compliance with the radiation protection standards for internal exposures. A monitoring programme to define airborne and water-borne off-site releases should be established.

9.3. RADIATION MONITORING

For external radiation exposure monitoring, workers should wear personal dosimeters when working in controlled areas, and all the doses should be recorded.

9.4. TRAFFIC CONTROL

A traffic control system should be established on-site to prevent vehicle accidents and to control the movement of wastes. When wastes are relocated to other sites, appropriate control programmes and documents, and emergency procedures, should be established for trucks and their operators.

Depending on the national regulatory requirements and contamination levels, all personnel, vehicles and equipment leaving controlled areas should be monitored and, if necessary, decontaminated to predetermined levels before release in order to prevent the spread of contamination off-site and to protect the public and the environment. Specific facilities should be provided for the decontamination of vehicles, equipment and personnel and for workers to change and shower. These may already be available from the operational phase.

10. POST-CLOSEOUT MONITORING AND SURVEILLANCE PROGRAMMES

After the decommissioning/closeout of a mine/mill complex has been completed, owners will, for a number of years, have to demonstrate to the regulatory authorities that the closed out facilities are performing as designed and releases of contaminants from the site are below the stipulated release criteria. To achieve this, a well designed monitoring/surveillance programme should be established:

(1) To measure the release rates of contaminants such as radon, tailings particles and leachate to the environment via aquatic and atmospheric pathways
(2) To measure the increases, if any, in radioactivity or other pollutants in the food chain as a result of such releases
To monitor the deterioration in tailings containment, erosion control features, vegetation, etc.

To identify and resolve the potential health/safety hazards

To reassure the public that the closed out mine/mill and waste impoundments are not a hazard.

The owner should then perform any maintenance or other remedial actions required to ensure that the closed out facilities meet the regulatory requirements. Once it has been demonstrated that the facilities are behaving as designed for the number of years agreed to by the owner and the regulator, the facility will, in many jurisdictions, become the responsibility of a government authority and the owner will have no further liability for the site.

The former owner or government agency responsible for the closed out facility in the short or long term should ensure that funds are available for the required monitoring/surveillance programme and any institutional control programme required to guarantee the integrity of the site [48, 49].

To design and set up an effective monitoring/surveillance plan that will ensure the long term safety of humans and the environment requires:

(a) Good baseline environmental data on the condition of the site and the surrounding area before the mine/mill was established (subsections 6.1 and 6.2)

(b) A good understanding of the release pathways from the closed out facility to humans and the environment, and the means to model and assess any releases (subsection 5.2)

(c) An understanding of the requirements for a post-closeout monitoring/surveillance programme.

These considerations and the post-closeout institutional control requirements are discussed in the following subsections.

10.1. BASELINE DATA

Two essential requirements for establishing a post-closeout monitoring programme are good baseline environmental data on the condition of the site and surrounding area before the mine/mill was established (subsection 6.1) and similar data after completion of the decommissioning/closeout activities. The baseline characterization programme at the end of the closeout activities should be similar to the initial one, except that baseline data on buried waste and dismantled facilities should be included.

When pre-operational baseline data is unavailable, for example, in the case of an old facility, it may be possible to obtain adequate data by making measurements
in nearby areas unaffected by the operation of facilities. However, in extrapolating this data for use on-site, it is important to recognize that conditions affecting baseline levels can vary significantly over short distances.

10.2. PATHWAY ANALYSIS

The importance of identifying all the potential pathways through which pollutants can reach the environment and humans during any phase of the life-cycle of a mine/mill facility is discussed in subsection 5.2.2. The general exposure pathways are also identified.

During the post-closeout monitoring/surveillance period, the potential pathways through which pollutants can reach the environment and humans are likely to be via radon emanation and/or seepage of contaminated liquids. In the medium to long term, the pollutants could reach humans through the following additional pathway scenarios, which should be considered in the safety analysis/assessment (subsection 5.2):

1. Human activities (e.g. construction and drilling for mineral resources or water)
2. Natural processes and events (e.g. erosion, groundwater movement and seismic events)
3. Internal tailings processes (e.g. pyrite oxidation, mechanical failures, differential settlements and cover cracking).

Definition of the key pathways to humans and the results of the safety analysis/assessment will be of great assistance in the development of the post-closeout monitoring/surveillance programme.

10.3. POST-CLOSEOUT MONITORING/SURVEILLANCE PROGRAMME

Upon completion of reclamation activities, an on-site and off-site inspection should be undertaken to verify that the work planned (Section 7) has been successfully completed as specified. A permanent record of this final closeout inspection, including photographic surveys, should be kept.

Following closeout of the mine/mill site, the owner should set up a monitoring/surveillance programme to obtain the data required to demonstrate to the regulatory authorities that the closed out facilities are stable and behaving as designed, that releases from the site and doses to humans via all pathways are acceptable and that environmental contamination is not exceeding regulatory standards. The programme also allows the operators to identify areas requiring remedial action.

The monitoring/surveillance programme for a particular facility will depend on many site specific factors, e.g. the climate, site location, robustness of the facilities,
waste impoundment designs, ore and waste rock volumes and mineralogy, population distribution and regulations. The design of such a programme should be based on a site specific safety analysis/assessment (subsection 5.2), the results of which will assist in identifying:

1. The critical radionuclides and chemical pollutants
2. The important pathways, doses to critical groups and collective doses
3. What should be sampled, sampling locations and sampling methodology
4. The critical components which, if they failed, could possibly result in large releases of pollutants, e.g. a tailings dam.

The following subsections describe the type of activities that should be carried out or the parameters that should be measured in a generic monitoring/surveillance programme.

The information should be of value as a list of items for mine owners developing this type of programme for a site specific situation. A site specific monitoring programme should be an integral part of the decommissioning/closeout proposal and should build on the monitoring programme used during the operational phase of the mine/mill.

The schedule for surveillance of facilities and sampling will be dictated by the stability and performance of engineered work such as containment structures, covers and underground mine opening closures, the success of reclamation activities and the remoteness of the facility. The schedule should be reviewed annually to determine if changes in frequency, sampling location, etc. should be made.

The typical categories of monitoring/surveillance for closed out facilities include water quality monitoring, atmospheric monitoring, rehabilitation surveillance and biological monitoring [49].

10.3.1. Water quality monitoring

Monitoring should be carried out to determine the quality of surface water, groundwater and tailings pore water in order to investigate the potential for short and long term contamination by leachate.

10.3.1.1. Surface water

Surface water may be used for drinking and irrigation and could be a major pathway to human exposure. Monitoring should be directed towards surface waters that pass through or close to impoundments and piles which could be subject to drainage or which could be affected by the failure of containment structures. The maximum distance from tailings and other disposal areas at which surface waters should be sampled will depend on the proximity of humans and the exposure scenarios. Both water quality monitoring and biological monitoring of nearby streams should be carried out at appropriate intervals.
10.3.1.2. **Groundwater**

Groundwater monitoring near closed out heap leach piles, tailings and other waste sites and mines is normally conducted when the subsurface movement of contaminated water represents a potential pathway to important aquifer(s) and wells for drinking water in the immediate vicinity. The layout of monitoring wells requires knowledge of the hydraulic gradient. This can be anticipated from the topography and local subsurface geology at the site and may require confirmation by injection of tracers into upgradient boreholes. Usually, at least two monitoring wells, upgradient and downgradient of the potential contamination source, are required.

10.3.1.3. **Tailings pore water**

Monitoring of tailings pore water might be required to chart the migration of radionuclides and chemicals from tailings into surface runoff, infiltration and seepage.

10.3.1.4. **Frequency of water sampling**

The frequency of water sampling is very site specific. Typically, samples are taken quarterly during the first year to determine the seasonal effects. The frequency of sampling in subsequent years decreases (if there is no adverse migration of pollutants) as a greater understanding of the closed out system is achieved and confidence in the stability of impoundments is gained.

10.3.2. **Atmospheric monitoring**

Atmospheric monitoring programmes generally focus on two parameters: airborne particulate matter, and radon and its daughters. The following discussion describes the monitoring considerations during and after decommissioning/closeout.

10.3.2.1. **Establishing an atmospheric monitoring programme**

To establish a programme for measuring concentrations of airborne particles and ambient radon, site specific meteorological data should be collected if it is not available from the operational phase. The location of sampling points should be determined during the pre-operational and operational phases, taking into account the annual wind speed and direction frequencies. Points should surround the sites and a significant number should be clustered along the dominant annual or seasonal wind vector, downwind of the site. The barometric pressure, atmospheric stability, rainfall and temperature should accompany each set of air quality sampling measurements.
10.3.2.2. Airborne particulate matter

Contaminated particles can become airborne at a tailings impoundment or mining debris pile. The main concern, other than crystalline silica in some locations, is radioactive particles, which could be an important pathway for inhaled radioactivity. Most radioactive particles contain members of the $^{238}\text{U}$ decay series, but where $^{232}\text{Th}$ is present in significant quantities members of its decay series may also be present.

For the purpose of estimating doses from radioactive constituents, the ‘respirable’ particle size fraction is of particular concern.

Airborne particles should be analysed for natural uranium, $^{230}\text{Th}$, $^{226}\text{Ra}$ and $^{210}\text{Pb}$. Where the $^{232}\text{Th}$ content is a significant fraction of the uranium content, analyses should be extended to include $^{228}\text{Th}$, $^{232}\text{Th}$ and $^{228}\text{Ra}$. If the processed ore contains significant levels of heavy metals or crystalline silica, analyses for the metals and for respirable crystalline silica may also be required.

10.3.2.3. Radon gas

A monitoring programme for radon gas usually consists of ambient air concentration sampling at the same locations as those where particulates were sampled and exhalation measurements taken on the disposal sites. Measurement of ambient radon can be used to quantify the health risk to critical receptors due to radon daughters.

Ambient radon can be measured using devices that analyse grab samples virtually instantaneously, or by passive monitoring methods that measure the average ambient concentrations over several weeks [8]. The timing of sampling should coincide with that of radon flux sampling. Data on the radon emanation coefficient may also be collected. Active monitoring instrumentation can be used to measure short lived alpha radon daughters directly by making a continuous, integrated count of individual radionuclides.

Radon exhalation data from bare surfaces may be required as input for risk assessment and to assess the need for and type of remedial action necessary to minimize this flux from sites in the long term. Exhalation data from the pre-operational and operational phases provide the basis for evaluating the effectiveness of reclamation techniques applied during closeout.

The exhalation rate is usually measured by inverting a cylindrical container with one open end on to the surface and measuring the increase in concentration of radon within it. A network of exhalation sampling points should be established to provide data representative of the surface.

Moisture content and temperature are important considerations in monitoring programme design. If appropriate, different weather conditions and seasons should be included in the programme.
10.3.3. Rehabilitation surveillance

Aerial or ground level surveillance should be carried out to determine if waste containment, erosion control and other remedial measures are still effective. Ground surveys are more accurate and provide detailed information; in any case, they are required for sample taking.

If the closed out site is in a remote area and there is no established base, aerial surveillance and analysis of aerial photographs might be relied on heavily, with less frequent ground surveys to confirm the aerial investigations. In more accessible areas, the most cost effective and efficient plan calls for more frequent ground surveillance, supplemented by aerial surveillance (which is more expensive) to assess large scale events.

Aerial surveillance and interpretation of aerial photographs can be used to examine problems such as erosion, serious intrusion, cover shrinkage and damage, differential settling, the effects of flooding, dam or slope failure and streaming. Ground surveillance can be used to detect all the above problems and to observe the resulting damage in detail.

10.3.4. Biological monitoring

Biological monitoring should be carried out to determine if contaminants are increasing in the food chain as a result of atmospheric or water pathways. Samples of aquatic biota, e.g. fish, which might be consumed by humans in areas downstream of the closed out site, as well as vegetation samples at air sampling stations, should be collected. Typically, biological samples should be collected every few years.

10.4. POST-CLOSEOUT INSTITUTIONAL CONTROLS

Institutional controls may be required after the closeout of a mine/mill complex to prevent intrusion into the waste repository; to prevent removal of or interference with the waste; to ensure that the performance of the repository meets the design criteria; and to ensure that necessary remedial actions are carried out.

The controls can be active (e.g. periodic inspection, maintenance or controlled access) or passive (e.g. permanent markers, land use regulations).

The maximum duration of institutional controls for which the designer can take credit in his safety assessment should be determined by the regulatory authority, where necessary in co-operation with other countries and international agencies.
11. COST ESTIMATING AND FINANCING FOR DECOMMISSIONING/CLOSEOUT

The cost to decommission/close out a uranium mine/mill facility is very site specific. For mill sites, the tailings management scheme and the remoteness of the site are major factors affecting the costs. Advanced planning during the mine/mill licensing and design phase can facilitate decommissioning/closeout of the mine/mill complex and substantially lower the total cost.

The total cost is also a function of the need for on-site/off-site monitoring and surveillance programmes during and after decommissioning/closeout (Section 10) and of the possible future need for remedial work, including vicinity property remediation. This later requirement is critically important, because future generations may have to pay for remedial work if the sites have not been decommissioned or closed out adequately.

11.1. FINANCING ALTERNATIVES

Owners of private mines/mills operating under licences issued by a regulatory authority may be required to establish a financial instrument adequate to cover the decommissioning/closeout costs as well as the anticipated post-closeout monitoring, maintenance and remediation costs. It is important that the required funds be set aside during the revenue producing years of the mine/mill facility. These financial instruments can take on many forms, e.g. unit of production levies, bonds and net worth escrow accounts. The appropriate mechanism(s) should be established in consultation with the competent authority in the Member State.

Funding for the decommissioning/closeout of state owned or abandoned facilities usually has to be provided by the state. Since funding appropriation requires legislative authorization in many Member States, and the authorization may be politically sensitive, the amount of money allocated may vary from year to year because of competing national issues. Variable funding levels could result in inefficiency and costs that are significantly higher than a consistent funding and work plan.

11.2. DECOMMISSIONING/CLOSEOUT COSTS

Reference [50] presents several case studies of actual costs incurred in the decommissioning/closeout of Canadian mine/mill complexes and compares them with generic cost estimates. The costs cited in this reference show large variations from site to site, indicating the highly site specific dependence of costs.
Table II shows the costs for decommissioning uranium mines/mills in the USA. The wide range of values in the table reflects both site specific and institutional factors unique to the US experience. The high cost for federally funded tailings disposal primarily results from the need to relocate more than half the tailings from unsuitable sites to better locations. The costs include planning, design, environmental documentation, research and development, construction, certification and interim surveillance and maintenance.

The costs for decommissioning/closeout of mines/mills and waste management/disposal facilities may vary greatly in Member States according to site specific factors. Higher costs can be expected when tailings or mining debris have to be relocated. On the other hand, if tailings can be stabilized on-site significantly lower costs may result. Annex VI provides, inter alia, information on the costs of selected decommissioning/closeout exercises.

12. DOCUMENTATION FOR DECOMMISSIONING/CLOSEOUT

Before the final shutdown of a mine/mill facility, a document outlining the major aspects related to the planning, design, technology and implementation of the decommissioning/closeout programme would be submitted to the regulatory authorities in support of the application for a licence to proceed with the programme. The type of information included in this document is given in subsection 7.1.
During implementation of the decommissioning/closeout programme, detailed records of all significant activities should be maintained by the implementing organization. At the end of the programme, a completion report should be submitted to the regulatory authorities. The report may contain:

(1) Construction details such as final drawings and specifications, photographs of the structures at predetermined stages of construction and a record of construction testing
(2) The exact location of all types of radioactive and toxic chemical waste disposal facilities
(3) The location of the closed out in situ leach facilities
(4) A record of measurements that confirm compliance with cleanup criteria
(5) A materials balance analysis
(6) A record of QA audits and construction inspections
(7) The lessons learned, which may be of value in future operations
(8) Evidence of deed and title with ownership responsibility
(9) A record of all interactions with the regulatory authority.

This information represents all records that demonstrate adequate performance of the work. In conjunction with the long term maintenance and surveillance plan, this information may be used by the regulatory authority as the basis for issuance of a certification that releases the owner from further liability.

13. QA PROGRAMME FOR DECOMMISSIONING/CLOSEOUT

QA is defined as the planned and systematic actions and controls that are undertaken to prove that a structure or system will perform satisfactorily. The QA actions also provide adequate confidence in the validity and integrity of the reported data, methods and procedures, as well as in the protection, retrievability and replicability of the data.

The purpose of a QA programme is to ensure that appropriate controls are in place so that the performance objectives and technical requirements are achieved. The QA programme should be established before decommissioning activities start so that it can be used for all activities, including site characterization, planning, design, construction, monitoring, and long term surveillance and maintenance, providing a high level of confidence that all activities are implemented as planned.
Elements of a comprehensive QA programme are presented in Refs [51–55]. However, the level and resources with which a QA programme is applied will depend to a large extent on national regulations as well as on the project in question. In general, a QA programme should include the following considerations.

13.1. ORGANIZATION

The authority and duties of those persons and organizations responsible for performing activities covered by a QA programme should be clearly established in writing. Such persons and organizations should have sufficient authority and organizational freedom to be able to identify problems, initiate solutions and verify implementation of solutions.

13.2. DESIGN CONTROL

A documented design control system should include measures, such as a peer design review, to verify the adequacy of the design; controls to ensure that the data used in the design work were collected in a defined and verifiable manner; measures to verify and validate the computer software used in the design activities; and measures to ensure that verification or checking is performed by individuals different from those who developed the original design: design changes should be controlled in a similar manner. The positions and organizations responsible for design verification should also be included in the design control system.

13.3. INSTRUCTIONS, PROCEDURES AND DRAWINGS

Procedures need to be established in order to delineate clearly the sequence of actions to be performed in the preparation, review, approval and control of instructions, procedures and drawings.

13.4. DOCUMENT CONTROL

Documents that contain site characterization, planning, design, construction, monitoring, maintenance and other critical requirements should be controlled during their approval, issuance and distribution to ensure that the directions are understandable and that the documents reach those responsible for the activities. The contents of these documents should be reviewed and controlled to ensure that they are adequate and that the quality requirements are appropriately stated.
13.5. MATERIALS, PARTS, COMPONENTS AND SAMPLES

Measures should be established for identifying and controlling materials, parts, components, and field and laboratory samples.

13.6. INSPECTION

A programme for inspecting the results of activities affecting quality, for the purpose of acceptance or rejection, should be implemented. This should include criteria for acceptance to verify conformance with the approved documents and requirements.

13.7. TEST CONTROL

A programme should be established to ensure that all testing is performed according to written procedures that incorporate the requirements from approved documents. All measurement and test equipment should be controlled, calibrated, maintained and adjusted as appropriate. The test results should be documented and retained. All laboratories, whether part of the organization or under subcontract, must be subject to the same requirements and be audited periodically to verify compliance.

13.8. NON-CONFORMANCE

Measures should be established to ensure that conditions adverse to quality, such as failures, malfunctions, defects and non-conformance, are promptly identified and corrected.

13.9. QA RECORDS

The maintained QA records should include the results of reviews, inspections, tests and audits and the qualifications of personnel, procedures and equipment to show that activities affecting quality have been performed properly.
14. SUMMARY AND CONCLUSIONS

14.1. SUMMARY

(1) During the 1980s, many uranium mines/mills were closed, since they had reached the end of their useful life. More are being closed as uranium production becomes unprofitable because of lower prices resulting from a decrease in demand and an abundant supply and, to a certain extent, because of the higher cost of providing measures that are consistent with society’s current expectations in environmental protection.

(2) Mining and milling of radioactive ores result in contaminated buildings and facilities that should be decommissioned, as well as in large quantities of tailings and other residues that should be closed out safely so that residual environmental and health risks do not exceed acceptable levels.

(3) This report provides information to Member States in order to assist in planning and implementing the decommissioning/closeout of uranium mines/mills, tailings impoundments and other debris. Most of the information applies to the decommissioning/closeout of mines/mills for thorium bearing ores.

(4) The report reviews factors that are important to decommissioning/closeout, including regulatory and safety analysis considerations; planning and technical considerations related to the decommissioning/closeout of all components of a mine/mill complex; restoration of vicinity properties and groundwater; radiation protection, health and safety programmes; costs; post-closeout monitoring/surveillance; and the equipment and methods required to carry out these activities.

14.2. CONCLUSIONS

On the basis of the data presented in this report and in associated IAEA reports, the following general conclusions can be made regarding the decommissioning/closeout of uranium mine/mill complexes:

(1) The decommissioning/closeout of a mine/mill complex can best be addressed on a site specific basis because of the diversity of site conditions and the magnitude of operations; the variety of mining methods, e.g. underground and open pit; the different extraction processes, e.g. acid, alkaline and solvent; and the range of proposed uses for the site.

(2) Local factors such as national priorities, climate, hydrology and the potential for flooding could have a great effect on planning. Issues dominant at one site may be unimportant at other sites, e.g. precipitation. While the experience of
others is valuable, practices and standards that are accepted elsewhere for the design or performance of work should not be adopted without site specific assessment and optimization.

(3) The decommissioning/closeout of a mine/mill can often be accomplished by a variety of approaches.

(4) The promulgation of effective safety and health regulations in Member States and measures by the industry to limit adverse environmental and health effects has demonstrated that the decommissioning of uranium mines/mills and the closeout of uranium tailings and other residues can be carried out safely and with acceptable impacts.

(5) The methods and techniques needed to safely decommission the buildings, structures and equipment in a mine/mill complex and close out tailings impoundments and other residues are available.

(6) Because of the very long half-lives of the predominant isotopes, there are still open issues regarding the long term closeout of impoundments for tailings and other residues from the mining and milling of radioactive ores.

(7) Use of the containment capabilities of the natural environment, e.g. disposal in a deep underground mine or lake, for long term containment of tailings seems technically promising.

(8) Planning for the decommissioning/closeout of new uranium mine/mill facilities should start during the design phase and continue during the operational phase. This planning should culminate in the implementation of an optimized plan that is approved by the regulatory authority, includes site specific considerations, and ensures protection of the health and safety of humans and of the environment.
Annex I

EXAMPLES OF NATIONAL REGULATORY REQUIREMENTS, REGULATIONS AND CRITERIA FOR MILL TAILINGS AND THE DECOMMISSIONING/CLOSEOUT OF URANIUM MINES/MILLS

Note

The following examples illustrate various national approaches, the range extending from a generic, prescriptive approach to a site specific methodology. Therefore, it is not prudent to compare national practices on all items.

Example 1: Environmental Protection Agency (EPA) Standards, USA

Example 2: Generic Requirements of the Regulatory Authorities in Canada

Example 3: French Regulations: Decree No. 90-222 dated 9 March 1990
Example 1

EPA Standards, USA$^{1,2}$

PART 192 — HEALTH AND ENVIRONMENTAL PROTECTION STANDARDS FOR URANIUM MILL TAILINGS.

SUBPART A — Standards for the Control of Residual Radioactive Materials from Inactive Processing Sites

192.02: Standards

Control shall be designed:

(1) To be effective for up to 1000 years, to the extent reasonably achievable, and, in any case, for at least 200 years,

(2) To provide reasonable assurance that releases of $^{222}$Rn from residual radioactive material to the atmosphere will not:

(a) Exceed an average release rate of 0.74 Bq (20 pCi)·m$^{-2}$·s$^{-1}$, or

(b) Increase the annual average concentration of $^{222}$Rn in air at or above any location outside the disposal site by more than 0.02 Bq (0.5 pCi)/L.

SUBPART B — Standards for the Cleanup of Land and Buildings Contaminated with Residual Radioactive Materials from Inactive Uranium Processing Sites

192.12: Standards

Remedial actions shall be conducted so as to provide reasonable assurance that, as a result of residual radioactive materials from any designated processing site:

(1) The concentration of $^{226}$Ra in land averaged over any area of 100 m$^2$ shall not exceed the background level by more than:

(a) 0.18 Bq/g (5 pCi/g), averaged over the first 15 cm of soil below the surface, and

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(b) 0.55 Bq/g (15 pCi/g), averaged over 15 cm thick layers of soil more than 15 cm below the surface.

(2) In any occupied or habitable building:

(a) The objective of remedial action shall be, and reasonable effort shall be made to achieve, an annual average (or equivalent) radon decay product concentration (including background) not to exceed 0.02 working levels (WL). In any case, the radon decay product concentration (including background) shall not exceed 0.03 WL, and

(b) The level of gamma radiation shall not exceed the background level by more than 20 \(\mu\)R/h (1 R = \(2.58 \times 10^{-4}\) C/kg).

192.20: Guidance for implementation

Remedial action will be performed with the “concurrence of the Nuclear Regulatory Commission and the full participation of any state that pays part of the cost” and in consultation, as appropriate, with other government agencies.

192.21: Criteria for applying supplemental standards

The implementing agencies may apply standards in lieu of the standards of Subparts A or B if certain circumstances exist, as defined in 192.21.

192.22: Supplemental standards

“Federal agencies implementing Subparts A and B may in lieu thereof proceed pursuant to this section with respect to generic or individual situations meeting the eligibility requirements of 192.21.”

(1) “... the implementing agencies shall select and perform remedial actions that come as close to meeting the otherwise applicable standards as is reasonable under the circumstances.”

(2) “... remedial actions shall, in addition to satisfying the standards of Subparts A and B, reduce other residual radioactivity to levels that are as low as is reasonably achievable.”

(3) “The implementing agencies may make general determinations concerning remedial actions under this Section that will apply to all locations with specified characteristics, or they may make a determination for a specific location. When remedial actions are proposed under this Section for a specific location, the Department of Energy shall inform any private owners and occupants of the affected location and solicit their comments. The Department of Energy shall provide any such comments to the other implementing agencies [and] shall also periodically inform the Environmental Protection Agency of both general and individual determinations under the provisions of this section.”
Example 2

Generic Requirements
of the Regulatory Authorities in Canada³

The following generic requirements are a summary of the global regulatory requirements in Canada.

(1) **Radon control**

There are no specific requirements for radon control. The need for radon control is determined through an environmental pathway analysis. If radon is a major exposure pathway (which in Canada has not been the case to date), the requirements may be determined through a cost–benefit analysis. Although direct control for radon may not be required, the Atomic Energy Control Board (AECB) has also stated that radon control should be considered when designing other reclamation work such as gamma radiation attenuation cover.

(2) **Attenuation of gamma fields**

There are no specific requirements for attenuating gamma fields. With the decommissioning of the Beaverlodge uranium mine, the AECB did require surface gamma fields to be reduced to 2.5 μSv/h, with further reductions to be based on ALARA. In other facilities, this requirement has been further reduced to 1.0 μSv/h.

(3) **Spills**

As a general rule, tailings spills should be excavated and disposed of in the tailings area. A proponent may propose to leave the spills in place if it can be demonstrated that their presence represents minimal concern; that their removal would cause excessive environmental damage; or that the cost for removal and relocation exceeds the benefits. Therefore, each spill should be treated on a site specific basis.

(4) **Dam stability/engineering principles**

It is recognized that structures have a finite lifetime and degrade over time. With this in mind, the AECB has not dictated any definitive criteria for downstream slopes, etc. The following general conditions are imposed for structures:

(a) Use of passive barriers, natural or engineered, should be maximized to control radioactive and non-radioactive releases from the closed out site

(b) Use of containment systems that may be subject to abrupt degradation of performance should be minimized and preference should be given to systems that only degrade gradually

(c) All containment systems must be evaluated in terms of their long term performance and durability; reliance on maintenance should be minimized.

(5) Effluent releases

Containment discharges from a decommissioned facility would normally be required to meet some site specific limits based on a pathway analysis. These discharges should not exceed on a mass load/unit time basis those discharges that took place during operations. Furthermore, provincial water quality objectives would be required to be met at designated points.

(6) Seepage control

Control of seepages is a highly site specific requirement. Where seepages result in unacceptable levels of downstream contamination, controls are required. On the other hand, it may be advantageous to allow infiltrating waters to exist as seepage, thus taking advantage of the retardation capabilities of local natural materials.

(7) Long term care

It may not be economically practical to implement a decommissioning plan that permits the site to be abandoned. For these specific applications, a long term storage option may be practical. AECB Consultative Document C-90 states that “controls which require ongoing human intervention (as would be required for effluent treatment) will not be acceptable”.

(8) Institutional controls

Institutional controls are recognized as a most likely requirement for abandoned uranium mill tailings areas. The need for controls must be justified and demonstrated through a cost–benefit analysis.
Example 3

French Regulations: Decree No. 90-222 dated 9 March 1990

This decree was drawn up on the basis of the French mining code, the Euratom directives, the French decree concerning the general principles of protection against ionizing radiation, itself based on the recommendations of the International Commission on Radiological Protection (ICRP) and the directives of the European Union. It was submitted for approval to the Central Service for Protection Against Ionizing Radiation (Ministry of Health) and the General Council of Mines. The decree adopted part of the section on the General Instructions for the Mining Industry (RGIE) entitled Ionizing Radiation.

(1) Applicability

"The provisions of this section are applicable to uranium mines and mills, surface installations and legal ancillaries of facilities where radioactive substances are utilized" (Art. 2).

The decree only relates to products with a uranium content greater than 0.03% (Art. 8).

"The mine and mill facilities must be the subject of surveillance by the operator throughout the duration of the work and afterwards until it is proved that its radiological impact on the environment is acceptable." Monitoring must last for at least 1 year after closure of the site.

(2) Criteria for radiological protection of the population

"Work must be carried out in such a manner that its radiological impact on the environment is as low as reasonably achievable, both while the facility is open and after its final closure" (Art. 3). The means to implement safety measures and monitoring are to be determined by those personnel in charge of the site.

Limitation of annual individual exposure: The operator must prove that the individual dose is less than 5 mSv/a in addition to natural exposure (Arts 6 and 7 — in accordance with ICRP recommendations). To this end the operator must:

(a) Identify the main radionuclides or forms of radiation liable to be released by the sources
(b) Identify the main pathways of transfer liable to lead to members of the critical group in the immediate vicinity and/or on the site

(c) Continuously take readings by means of fixed stations in the transfer pathways and the surrounding region (to assess the natural levels).

(d) Establish a reasonable exposure scenario.

(e) Take into consideration for internal exposure that:

(i) A rough estimate can be made by assuming that drinking water represents the only transfer pathway by ingestion and that individuals who are most exposed drink 2.2 L of water per day, taken from the receiving water course immediately after dilution of releases (Appendix, Art. 7).

(ii) Regarding breathing, an individual from the public is assumed to inhale 0.8 m$^3$ of air per hour (Appendix, Art. 6).

(f) Sum the principal additional exposures identified, the annual limits being those recommended by the ICRP (sum <5 mSv/a in addition to natural exposure).

(3) Release verification and environmental monitoring after closure of uranium mining sites

Administrative constraints are introduced for discharges. A surveillance network is prescribed to ascertain any possible environmental contamination. After site closure, the following procedure applies:

(a) Identify the transfer pathways that remain.

(b) Identify the characteristic parameters to be monitored.

(c) If water contaminated with $^{226}$Ra continues to be released (Art. 9), then release of water:

(i) with less than 740 Bq/m$^3$ is authorized without treatment

(ii) between 740 and 3700 Bq/m$^3$ requires no treatment in situ but dilution by a factor of at least 5 in the receiving waterway

(iii) of more than 3700 Bq/m$^3$ requires mandatory treatment.

(d) Measurements must be made for monitoring the natural environment at frequencies corresponding to the size of the site and the results obtained (the main monitoring requirements are related to $^{226}$Ra and the uranium in water, alpha energy potential and gamma dose in air).

"The radiological impact on the environment is acceptable if the annual exposure limits prescribed in Art. 6 (following) are not exceeded" (Annex, Art. 8). "Annual limits for added exposure are as follows (Art. 6):

(i) 5 mSv for external exposure

(ii) 170 Bq for long lived alpha radionuclides from $^{238}$U as suspended matter in air"
(iii) 2 mJ of alpha potential energy for short life decay products of $^{222}$Rn in air that might be inhaled
(iv) 6 mJ of alpha potential energy for short life decay products of $^{220}$Rn in air
(v) 7 kBq for ingested $^{226}$Ra
(vi) 2 g for ingested uranium; the daily quantity of ingested hexavalent components should not exceed 150 mg."

"The annual total added exposure rate (Taux Annuel d'Exposition Totale Ajoutée — TAETA) for members of the public must be less than 1" (Art. 7).

(4) Administrative verification

"The Prefect may at any time require that the operator, at the latter's expense, has all or part of the measures verified by any individual or organization designated by the Prefect or by the Administration.

He may also, in the event of pollution accompanied by significant changes relative to the usual results of measurement, impose a reduction in the time intervals between the verifications planned and increase the frequency of submission of the results report" (Art. 18).
Annex II

EXAMPLES OF NATIONAL CRITERIA
FOR THE EXEMPTION, RELEASE OR CLEANUP
OF RADIOACTIVE SITES, BUILDINGS,
EQUIPMENT AND MATERIALS
FROM THE DECOMMISSIONING/CLOSEOUT
OF URANIUM MINES/MILLS

Example 1: French Exemption Levels Adopted for Specific Decommissioning Projects

Example 2: United States Nuclear Regulatory Commission (NRC): Acceptable Surface Contamination Levels for Uranium and Thorium

Example 3: NRC: Cleanup Criteria for Land and Soil

Example 4: Canadian Uranium Mine/Mill Material Salvage Decontamination Limits

Example 5: Recommendations of the Strahlenschutzkommission (SSK) (Germany) Concerning the Release of Solid Materials in the Decommissioning of Uranium Milling Facilities
Example 1

French Exemption Levels Adopted for Specific Decommissioning Projects\(^5,6\)

1. **Residual surface activity for premises to be used for non-nuclear industrial purposes**

   Fixed surface activity inside the premises shall not exceed 2 Bq/cm\(^2\) on average.\(^7\) A maximum value of 20 Bq/cm\(^2\) may be reached provided that the above average value is not exceeded over 1 m\(^2\). For outside surfaces, values are ten times higher. External exposure rates shall also be limited below the following values (at 30 cm from the surface): 7.5 \(\mu\)Gy/h for skin, beta exposure, and 1.2 \(\mu\)Gy/h for the whole body, gamma exposure.

2. **Residual surface activity for materials that may be released into the public domain**

   Materials that are permitted to be sold as scrap steel or reused by non-exposed workers are subject to the same regulations as those that apply inside the premises. On accessible parts, the average fixed surface activity shall not exceed 2 Bq/cm\(^2\). A maximum value of 20 Bq/cm\(^2\) may be reached provided that the average value of 2 Bq/cm\(^2\) is not exceeded over 1 m\(^2\). The external exposure rate shall not exceed 7.5 \(\mu\)Gy/h, beta exposure (at 30 cm from the surface), nor 1.2 \(\mu\)Gy/h, gamma exposure (at 30 cm), nor 15 \(\mu\)Gy/h, beta exposure, at contact on easily accessible parts.

3. **Residual soil specific activity for non-nuclear industrial use of the site**

   For surface layers between a depth of 0 and 50 cm, the gamma air dose rate, at 15 cm above the ground, shall not exceed 1 \(\mu\)Gy/h averaged over 1 m\(^2\). The gamma air dose rate, as measured at 1 m above the ground at the outside of the buildings, shall not exceed 0.5 \(\mu\)Gy/h averaged over 100 m\(^2\). Regarding layers between a depth of 0.5 and 3 m, the specific activity limits are set at \(3.7 \times 10^8\) Bq/t of \(^{238}\)U and \(1.8 \times 10^7\) Bq/t of \(^{226}\)Ra and \(^{228}\)Ra.

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5. Taken from reports approved by SCPRI (Central Service for Protection Against Ionizing Radiation) — Ministry of Health.

6. Some restrictions on use have been set for materials released from regulatory control.

7. All Bq/cm\(^2\) values measure alpha contamination.
Example 2

NRC: Acceptable Surface Contamination Levels for Uranium and Thorium\textsuperscript{8,9,10,11,12}

<table>
<thead>
<tr>
<th>Nuclides</th>
<th>Average</th>
<th>Maximum</th>
<th>Removable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural uranium (U-235, U-238) and associated decay products</td>
<td>0.8</td>
<td>2.5</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>(5000)</td>
<td>(15 000)</td>
<td>(1000)</td>
</tr>
<tr>
<td>Natural thorium and associated decay products</td>
<td>0.16</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>(1000)</td>
<td>(3000)</td>
<td>(20)</td>
</tr>
<tr>
<td>Beta–gamma emitters</td>
<td>0.8</td>
<td>2.5</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>(5000)</td>
<td>(15 000)</td>
<td>(1000)</td>
</tr>
</tbody>
</table>

\textsuperscript{8} Values are in Bq/cm\textsuperscript{2}; original values (in brackets) are in dis/min per 100 cm\textsuperscript{2}.

\textsuperscript{9} Where surface contamination is by both alpha and beta–gamma emitting nuclides, limits for each should apply independently.

\textsuperscript{10} Average and maximum radiation levels associated with surface contamination from beta–gamma emitters should not exceed 2 \(\mu\text{Gy/h}\) at 1 cm and 10 \(\mu\text{Gy/h}\) at 1 cm, respectively, measured through less than 7 mg/cm\textsuperscript{2} of total absorber.

\textsuperscript{11} The NRC is currently working on revised residual contamination limits for decommissioning based on radiation doses.

\textsuperscript{12} UNITED STATES NUCLEAR REGULATORY COMMISSION, Guidelines for Decontamination of Facilities and Equipment Prior to Release for Unrestricted Use or Termination of Licenses for Byproduct, Source or Special Nuclear Material, NRC, Washington, DC (1982).
Example 3

NRC: Cleanup Criteria for Land and Soil\textsuperscript{13,14}

<table>
<thead>
<tr>
<th>Nuclides</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural thorium (Th-232, Th-228) with daughters present and in equilibrium</td>
<td>0.4 (10)</td>
</tr>
<tr>
<td>Natural uranium (U-238, U-234) with daughters present and in equilibrium</td>
<td>0.4 (10)</td>
</tr>
<tr>
<td>Depleted uranium, natural uranium with daughters separated</td>
<td>1.4 (35)</td>
</tr>
<tr>
<td>Enriched uranium</td>
<td>1.2 (30)</td>
</tr>
</tbody>
</table>

\textsuperscript{13} Values are in Bq/g; original values (in brackets) are in pCi/g.

\textsuperscript{14} UNITED STATES NUCLEAR REGULATORY COMMISSION, Branch Technical Position on the Disposal of Residual Thorium or Uranium, 46FR52061-3, NRC, Washington, DC (1981).

Example 4

Canadian Uranium Mine/Mill Material Salvage Decontamination Limits

Materials, machinery and equipment to be salvaged and released to the public domain must be decontaminated so as to remove as much loose contamination as practicable from all surfaces. For accessible surfaces, residual contamination levels must be such that:

(1) The beta activity does not exceed $10^5$ Bq/m$^2$ averaged over an area of 300 cm$^2$

(2) The gamma dose rate measured at a distance of 1 m shall not exceed 0.5 $\mu$Gy/h above background.

Regulations also require the establishment and retention of records of various measurements.
Example 5

Recommendations of the SSK (Germany)
Concerning the Release of Solid Materials
in the Decommissioning of Uranium Milling Facilities

(1) Contaminated scraps

Applicability

- Contaminated scraps arising from the dismantling of uranium mining and milling facilities
- Scraps destined for recycling in a steel smelting plant

Maximum radioactivity level

- Total alpha surface activity below 0.5 Bq/cm²

Additional requirements

- Scraps are given directly to the scrap dealer or steel manufacturer
- Pieces that could be reused are destroyed prior to release
- Scraps are fractured into pieces of a size ready for acceptance by the smelting plant under radiologically safe conditions prior to release
- The procedure for determination of surface activity can take into account plausibility considerations

(2) Contaminated equipment

Applicability

- Contaminated equipment (vehicles, tools, machines, etc.) of uranium mining or milling facilities which is intended to be reused outside the uranium industry
- If contamination with mill tailings or uranium concentrates exists, the applicability has to be investigated for the particular case

Maximum radioactivity levels — Total alpha surface activity below 0.05 Bq/cm$^2$
   — If the contamination originates only from ore or waste rock material, it can be assumed that after cleaning of all surfaces (no visible dirt left) this requirement has on average been met; in this case, surface activity measurements are not necessary

(3) Contaminated buildings

Applicability — Reuse of buildings from inactive uranium mining or milling sites for industrial purposes

Requirements — Contamination originates only from ore or waste rock material
   — Inner surfaces are cleaned to the extent that no visible dirt is left
   — The gamma radiation level is below 0.3 $\mu$Sv/h in all rooms
   — Concentration of $^{222}$Rn in air does not exceed 250 Bq/m$^3$ in all rooms
   — Building rubble arising from later demolition of the building is treated as stated below

(4) Contaminated building rubble

Applicability — Building rubble arising from demolition of uranium mining and milling facilities
   — If contamination with mill tailings or uranium concentrates exists, the applicability has to be investigated for the particular case

Maximum radioactivity levels — Activity concentration of $^{238}$U decay chain\(^{16}\) below 0.2 Bq/g: unrestricted release for deposition at conventional waste dump is possible
   — Activity concentration of $^{238}$U decay chain\(^{16}\) between 0.2 and 1 Bq/g: deposition at already contaminated sites that are intended to be kept under regulatory control

\(^{16}\) Activity concentration of $^{238}$U decay chain: this term defines the specific activity of the individual nuclides of the $^{238}$U decay chain; if the nuclides are not in radioactive equilibrium, the nuclide with the highest activity has to be taken as reference.
— Activity concentration of $^{238}\text{U}$ decay chain $^{16}$ above 1 Bq/g: possibilities for the deposition have to be considered on a case by case basis

Additional requirements

— Recycling of materials with an activity concentration above 0.2 Bq/g has to be prevented

— Deposition sites for materials with an activity concentration above 0.2 Bq/g have to be reclaimed in accordance with recommendations for contaminated land (see item (5))

(5) Contaminated land

Applicability

— Contaminated sites from uranium mining and milling facilities

— Not included are waste rock piles, tailings impoundments and areas where the contamination originates from chemical uranium extraction processes

Maximum radioactivity levels

— Activity concentration of $^{238}\text{U}$ decay chain $^{16}$ below 0.2 Bq/g (averaged over 100 m$^2$ at depth intervals of 0–0.1, 0.1–0.5 and from 0.5 m down to the natural underground at intervals of 1 m): unrestricted use of site is possible

— Activity concentration of $^{238}\text{U}$ decay chain $^{16}$ above 0.2 Bq/g and below 1 Bq/g: the site can be used:
  — as forest or meadow without restrictions
  — as park with the restrictions that:
    — the gamma radiation levels have to be reduced to a maximum of 0.3 $\mu$Sv/h
    — sportsgrounds, kindergartens and other recreational facilities are only built on areas with a contamination level below 0.2 Bq/g
  — for industrial purposes with the restrictions that:
    — the gamma radiation levels have to be reduced to a maximum of 0.3 $\mu$Sv/h
    — dwelling houses, kindergartens and recreational facilities are only built on areas with a contamination level below 0.2 Bq/g
Additional requirements

— Activity concentration of $^{238}\text{U}$ decay chain\textsuperscript{16} above 1 Bq/g: necessity for reclamation and possibilities for land use should be investigated on a site specific basis

— For sites with an activity concentration above 0.2 Bq/g, it has to be ensured that no ground-water contamination occurs which can lead to radiation doses above 0.5 mSv/a

— All new buildings should be planned such that the $^{222}\text{Rn}$ concentration in air is below 250 Bq/m$^3$ inside the buildings

— For former mining or milling sites that are already used for different purposes, decisions should be based on site specific evaluation of the radiation doses

(6) Waste rock piles

Applicability

— Waste rock piles from uranium mining

— Not included are waste rock piles with elevated pyrite content, heap leach piles and piles containing tailings from metallurgical processes

Maximum radioactivity levels

— Activity concentration of $^{238}\text{U}$ decay chain\textsuperscript{16} below 0.2 Bq/g (averaged over 100 m$^2$ at depth intervals of 0-0.3, 0.3-3 and from 3 m down to the natural underground): no radiation protection measures have to be considered for the reclamation work

— Activity concentration of $^{238}\text{U}$ decay chain\textsuperscript{16} above 0.2 Bq/g and below 1 Bq/g or area of waste rock piles below 1 ha or volume of deposited material below $10^5$ m$^3$: no radiation protection measures have to be considered for the reclamation work, but future land use has to follow the recommendations for contaminated land (see item (5))

— Activity concentration of $^{238}\text{U}$ decay chain\textsuperscript{16} above 1 Bq/g or area of waste rock piles 1 ha or volume of deposited material above $10^5$ m$^3$: decisions on necessary reclamation measures and future land use should be based on site specific evaluation of the radiation doses.
Remarks

The philosophy underlying these recommendations can be characterized by the following statements:

(1) The radiation exposure that can originate from former uranium mining or milling sites is strongly dependent on the use of land. Therefore, standards for radioactivity levels have been derived on the basis of a generic pathway analysis for the different possibilities of land use. The parameters used in the calculation of radiation doses have been chosen to be as realistic as possible but are considered to be still conservative enough to cover the actual situations that are expected to occur in reality.

(2) The basis for the evaluation of radiation doses is the objective that doses to individuals should not exceed natural background doses by more than 1 mSv/a.

(3) The main goals of the recommendations are:
   (a) Definition of standards (contamination levels) below which no specific radiation protection measures have to be taken
   (b) Definition of standards below which no radiation hazards are to be expected if certain restrictions (mainly on land use) are followed.

(4) Since the generic assumptions that were made in the derivation of these standards are necessarily conservative, the situation at a particular site may be much more favourable. Therefore, these standards are not meant as targets for a cleanup programme. If contamination at a given site exceeds the standards, a site specific evaluation of the actual risks should be performed. This risk assessment should be the basis for decisions on reclamation work and future land use.
Annex III

GEOTECHNICAL, HYDROLOGICAL, ENVIRONMENTAL
AND ECONOMIC RATING MATRIX\textsuperscript{17}

In the event that the site of a uranium mine/mill is not a suitable long term
disposal location, a decision to relocate the contaminated material(s) may be made.
Selection of an alternative site should be based on a quantitatively defensible
analysis.

The latest phase in the selection of an alternative impoundment site consists of
ranking the sites based on specific characteristics. Annex III shows an example of
a rating matrix developed for the UMTRA Project in the USA with 35 attributes,
the criteria for allocating points and the weighting factors. It is not suggested that
the specific framework for scoring would necessarily be appropriate in other areas;
the information should be regarded only as an example of the method. The particular
criteria listed in the example may not be a sufficient or necessary listing for all
projects, but they may be a helpful checklist for some cases.

\textsuperscript{17} UNITED STATES DEPARTMENT OF ENERGY, Technical Approach Docu-
ment — Revision II, Document No. UMTRA-DOE/AL 050425.0002, DOE UMTRA Project

87
Geotechnical, Hydrological, Environmental and Economic Rating Matrix

<table>
<thead>
<tr>
<th>Factor:</th>
<th>Rank</th>
<th>Weight</th>
<th>Factor score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geotechnical</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>(1) Land slope (%)</td>
<td>&gt;10</td>
<td>5-10</td>
<td>2-5</td>
</tr>
<tr>
<td>(2) Surficial materials lithology</td>
<td>Gravel or sand</td>
<td>Very fine sand or sandy silt</td>
<td>Silt</td>
</tr>
<tr>
<td>(3) Surficial materials thickness (ft)</td>
<td>0-2</td>
<td>2-5</td>
<td>5-10</td>
</tr>
<tr>
<td>(4) Distance to nearest seismic risk capable fault (miles)</td>
<td>0.5-1.0</td>
<td>1-5</td>
<td>5-10</td>
</tr>
<tr>
<td>(5) Susceptibility to slope failures, subsidence or hydroconsolidation</td>
<td>Moderate to high</td>
<td>Low</td>
<td>Very low</td>
</tr>
<tr>
<td>(6) Present erosion</td>
<td>Intense gullying</td>
<td>Moderate gullying</td>
<td>Minor gullying</td>
</tr>
<tr>
<td>(7) Geomorphic stability</td>
<td>Very poor (fluvial environment)</td>
<td>Poor</td>
<td>Moderate</td>
</tr>
<tr>
<td>(8) Conflict with mineral resources</td>
<td>Serious conflicts</td>
<td>Moderate conflicts</td>
<td>No or minor conflicts</td>
</tr>
<tr>
<td>(9) Relative strength and compressibility of foundation soil and rock (only if rock is ranked less than 4)</td>
<td>Very soft or very loose</td>
<td>Soft or loose</td>
<td>Medium stiff to stiff or medium dense</td>
</tr>
<tr>
<td>Factor: Hydrological</td>
<td>Rank</td>
<td>Weight</td>
<td>Factor score</td>
</tr>
<tr>
<td>----------------------</td>
<td>------</td>
<td>--------</td>
<td>--------------</td>
</tr>
<tr>
<td>(10) Well yields are less than 150 gpd (Class III groundwater)</td>
<td>No</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(11) Background water quality (TDS in mg/L) and aquifer classification</td>
<td>&lt;1000</td>
<td>1000-2999</td>
<td>3000-4999</td>
</tr>
<tr>
<td>(12) Widespread ambient contamination (not due to activities at the processing site) that cannot be treated by public water supply systems</td>
<td>No</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(13) Upgradient groundwater contamination (above EPA MCLs) that affects local background</td>
<td>No</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Factor: Hydrological (cont.)</td>
<td>Rank</td>
<td>Weight Factor score</td>
<td></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>------</td>
<td>---------------------</td>
<td></td>
</tr>
<tr>
<td>(14) Geological strata where there is no existing groundwater and the strata are underlain by lithologies of relatively low hydraulic conductivity</td>
<td>No</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>(15) Volumetric flux of uppermost aquifer through cross-sectional area under disposal site (gpm); applies only if item (10) is 'no'</td>
<td>&lt;1</td>
<td>0</td>
<td>1–10</td>
</tr>
<tr>
<td>(16) Geochemical properties of aquifer and subsoils; CEC, ANC, IMOA and chemical reducing agents</td>
<td>None</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>(17) Potential for upward hydraulic gradients below a low hydraulic conductivity stratum</td>
<td>Downward</td>
<td>Neutral</td>
<td>Low</td>
</tr>
<tr>
<td>Factor:</td>
<td>Rank</td>
<td>Weight</td>
<td>Factor score&lt;sup&gt;19&lt;/sup&gt;</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>------</td>
<td>--------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Hydrological (cont.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(18) Proximity to point of groundwater discharge (ft)</td>
<td>None</td>
<td>&lt;500</td>
<td>500-300</td>
</tr>
<tr>
<td>(19) Depth to groundwater in shallowest aquifer (ft)</td>
<td>&lt;20</td>
<td>20-50</td>
<td>50-200</td>
</tr>
<tr>
<td>Environmental</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(20) Distance to nearest point of groundwater withdrawal from potentially affected aquifer (miles)</td>
<td>On-site</td>
<td>0-0.5</td>
<td>0.5-1.0</td>
</tr>
<tr>
<td>(21) Precipitation frequency (events per year of more than 1/8 inch)</td>
<td>&gt;100</td>
<td>100-75</td>
<td>75-50</td>
</tr>
<tr>
<td>Factor: Environmental (cont.)</td>
<td>Rank</td>
<td>Weight Factor score&lt;sup&gt;19&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>------------------------------</td>
<td>------</td>
<td>----------------------------------</td>
<td></td>
</tr>
<tr>
<td>(22) Total annual precipitation (inches)</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>(23) Annual pan evaporation (inches)</td>
<td>&gt;40</td>
<td>40-30</td>
<td>30-20</td>
</tr>
<tr>
<td>(24) Population density&lt;sup&gt;22&lt;/sup&gt;</td>
<td>Site is within 1 mile boundary of any size city or town</td>
<td>Site is within 1 mile of a subdivision</td>
<td>Site is within 1 mile of a proposed subdivision or projected residential growth area</td>
</tr>
<tr>
<td>(25) Transportation network&lt;sup&gt;22&lt;/sup&gt;</td>
<td>Traffic congestion very likely, accident potential enhanced</td>
<td>Traffic congestion likely, accident potential moderate</td>
<td>Traffic congestion unlikely, accident potential low</td>
</tr>
<tr>
<td>(26) Presence of cultural or historical sites</td>
<td>Nationally significant cultural sites are known to be present within a 2 mile radius</td>
<td>Cultural sites of minor importance have been found within a 1 mile radius</td>
<td>The area was known to be inhabited in prehistoric times</td>
</tr>
<tr>
<td>Factor: Environmental (cont.)</td>
<td>Rank</td>
<td>Weight Factor score&lt;sup&gt;19&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------</td>
<td>----------------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>(27)</strong> Threatened, endangered, or economically important species&lt;sup&gt;22&lt;/sup&gt;</td>
<td>0</td>
<td>Prior use of the area by threatened, endangered, or economically important species is established, although no recent (within 5 years) sightings have been made within a 2 mile radius.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>The area contains a suitable habitat for threatened, endangered, or economically important species.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>The area contains a suitable habitat for threatened, endangered, or economically important species; however, a similar habitat is abundant throughout the area.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>There are no known threatened, endangered, or economically important species within a 2 mile radius, nor is the habitat suitable for threatened or endangered species.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>(28)</strong> Scenic value&lt;sup&gt;22&lt;/sup&gt;</td>
<td>0</td>
<td>Site has high recreational use, or is along the travel corridor to areas frequented by tourists.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Site is clearly visible to the majority of town residents, or is visible from area scenic viewpoints.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Site is visible to residents of existing or planned subdivisions.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Site is not visible from high use areas, viewpoints or populated areas.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Site is not visible to any residents within the city limits, surrounding unincorporated areas or planned growth areas.</td>
<td></td>
</tr>
<tr>
<td>Rank</td>
<td>Factor: Environmental (cont.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>--------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>(29) Land use(^{22}) — current</td>
<td>A change in land use would directly affect the livelihood of the owner or surrounding owners</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>A change in land use would impact surrounding land owners</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>The site would disrupt existing use, but suitable adjacent land could be treated satisfactorily so as not to impact negatively the landowner’s economic base</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Current use of the site is considered low in productivity/quality relative to other areas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>A change in land use would have an insignificant effect on the existing or adjacent landowner or user</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>(30) Land use(^{22}) — potential</td>
<td>The area has potential for higher uses</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Adjacent land is suitable for development; presence of tailings would preclude desirability of other future adjacent land uses</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Land may have potential for development, but similarly suitable land is abundantly available in the area</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The area does not have potential for productive use without stimulation or change by humans</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Land has no recognized inherent value or potential</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{19}\) Weight Factor score
<table>
<thead>
<tr>
<th>Factor: Environmental (cont.)</th>
<th>Rank</th>
<th>Weight Factor score&lt;sup&gt;19&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>(31) Land ownership</td>
<td>Surface and sub-surface rights are owned by multiple, and different, parties</td>
<td>Surface rights are owned by multiple parties; subsurface rights are owned by a single party</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Factor: Economic</th>
<th>Rank</th>
<th>Weight Factor score&lt;sup&gt;19&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>(32) Distance from existing site</td>
<td>Longest</td>
<td>Moderate</td>
</tr>
<tr>
<td>(33) Distance to potential borrow sites: fine materials/coarse materials</td>
<td>Longest</td>
<td>Moderate</td>
</tr>
<tr>
<td>(34) Existing road network</td>
<td>Poor condition, extensive improvements required</td>
<td>Moderate condition, some improvements required</td>
</tr>
</tbody>
</table>
(cont.)

<table>
<thead>
<tr>
<th>Factor: Economic (cont.)</th>
<th>Rank</th>
<th>Weight</th>
<th>Factor score&lt;sup&gt;19&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>(35) Road has spots with positive gradients from mill site and tailings to disposal site (%)</td>
<td>&gt;10</td>
<td>8-10</td>
<td>0 to &lt;8</td>
</tr>
</tbody>
</table>

18 1 ft = 3.048 x 10^-1 m; 1 mile = 1.609 km; gpd = gallons per day (1 gal(US) = 3.785 x 10^-3 m^3); TDS = total dissolved solids; MCL = maximum concentration level; gpm = gallons per minute; CEC = cation exchange capacity; ANC = acid neutralization capacity; IMOA = iron and manganese oxide absorbents; 1 inch = 2.54 x 10^1 mm.

19 Factor score = rank x weight.

20 Refers to capable fault as defined by 10 CFR 100, Annex A (United States Code of Federal Regulations).

21 Determination of susceptibility is based on evidence of recent slope failures, subsurface materials and subsurface conditions.

22 If more than one ranking definition applies, the site would be ranked for the lowest point value.
Annex IV

CHECKLIST FOR REVEGETATION
OF DECOMMISSIONED URANIUM TAILINGS

This checklist is for revegetation in the closeout option where the tailings impoundment is capped with a multilayer protective layer.

(1) Assessment of the vegetation growing in the vicinity of the mine site to determine whether local species are suitable for rehabilitated tailings

(2) Characterization of the site and available materials (overburden and top soil) for physical, chemical and biological characteristics that might influence the selection of vegetation species

(3) Assessment of species for root growth patterns to judge their suitability to the tailings site from the point of view of root penetration

(4) Documentation of the succession of natural species to assess whether the established species will have long term viability, and if special management strategies would be required

(5) Selection of plant species on the basis of their ability to limit erosion and their potential to penetrate capping material; grasses may provide better erosion control than trees, and the roots of grasses are less likely to penetrate tailings capping

(6) Carrying out of greenhouse and field experiments might be necessary to test selected species for their tolerance to uranium and other toxicants, and their need for nutrients

(7) Modelling of the effect of the selected vegetation on the hydrology of the tailings impoundment

(8) Selection of species with a root system that is sufficient to protect the surface from wind erosion, but at the same time one that is not deep enough to penetrate the capping

(9) Assessment of the role of fauna, e.g. ants, termites, rodents and lizards, in disturbing the soil and causing erosion; the interrelationship between the fauna and the vegetation also requires assessment

(10) Compaction of capping material to ensure that the roots cannot penetrate; treating the capping material with chemicals that retard root penetration might warrant investigation

(11) Evaluation of the need to use artificial cultures of symbiotic microorganisms, e.g. rhizobia and mycorrhizas, to assist in nutrient cycling and to encourage rapid establishment of vegetation

(12) Assessment of the uptake and accumulation of radionuclides and micronutrients in the selected species
(13) Selection of species suitable for maintaining biodiversity and promoting ecosystem development might be necessary to restore the site to near pristine condition.

(14) Assessment of the effects of fire, cyclones, droughts, flooding and other natural events on the established vegetation before final selection of species.

(15) Monitoring of the established vegetation for its growth, elemental composition, root distribution and seeding characteristics at different time periods to assess long term success.

(16) Assessment of the rate of return of fauna may be necessary in the monitoring programme if the objective is for the site to be restored to a pre-existing natural ecosystem.
Annex V

LONGEVITY REQUIREMENTS

Note

The issue of longevity represents one of the most important considerations in the planning of containment structures. The suggested methodology is a contribution solving this issue. However, the difficulty in modelling individual design element responses within specified probabilities might make this methodology unsuitable for application across the diverse social, environmental and political systems that constitute the IAEA Member States.

Degradation of the closed out works over time is likely to lead to environmental impacts from erosion products, from surface water drainage, infiltration and subsurface seepages, acid generation, radon release and particulate dispersion by wind, containment failure, and from direct gamma radiation and dust inhalation. The magnitude of each of these factors is likely to vary for different containment options and will almost certainly vary as a function of time.

While the hazards and risks associated with uranium mill tailings and other uranium affected mining debris are not confined to their radioactive nature, it is this feature which puts this material into a particular area of concern. The radiological component of these risks will diminish only slowly with time, its magnitude being determined, in the case of uranium tailings, by the residual amount of the long lived radionuclide $^{230}$Th (half-life 77 000 years), provided that the amount of unrecovered uranium in the tailings is small. On this basis, the residual radioactivity of the tailings would reduce to about 10% of its initial value in 250 000 years and to about 1% in a little over 500 000 years.

The time-scales involved are too long for engineers to be able to give meaningful assurances on the performance of structures, or to establish criteria for designs that provide for the continuing integrity of constructed works. While confidence in the performance of any engineered structure to design specifications might be limited to hundreds of years, there is reasonable expectation that isolation of tailings over some thousands of years might be achievable.

However, there are fundamental problems in the predictive modelling of the performance of tailings disposal options over hundreds of thousands of years, since many of the factors influencing the possible impact on the environment are unknown or cannot be predicted reliably. These factors include climate change, seismic activity, sea level changes, hostilities, sabotage, major population changes, community wishes, technological standards, etc. Because of the inherent uncertainties, there
would seem to be little prospect of a useful outcome in modelling options for the
closeout of uranium mill tailings for periods of the order of hundreds of thousands
of years, as might be indicated by the half-life of $^{230}\text{Th}$.

While acknowledging that modelling is likely to become unrealistic over
periods of hundreds of thousands of years, assessments might reasonably be
attempted for periods of thousands, or even tens of thousands, of years. Such con-
siderations have led the international community to advance a number of different
corcepts on the time-scales applicable to tailings impoundments, to the design
criteria to be adopted and to the technically based expectations for performance in
terms of tailings containment. Some of the nationally and internationally formulated
regulatory guidelines on these issues are summarized as follows:

(1) IAEA Technical Reports Series No. 209 calls for impoundments to operate to
design for the order of 100 years and for the containment structure to remain
essentially unaffected by geomorphological and climatological processes for up
to 10 000 years

(2) AECB Regulatory Document R-104 concludes that the period for demonstrat-
ing compliance with individual risk requirements using predictive mathemat-
cal models need not exceed 10 000 years

(3) The NRC in 10 CFR Appendix A requires that the containment design provides
reasonable assurance of control of radiological hazards to be effective for
1000 years, to the extent reasonably achievable, and, in any case, for at least
200 years

IAEA Technical Reports Series No. 209 has been superseded by the newly pub-
lished Technical Reports Series No. 335 [3], which reads:

"The most advanced engineering design practice for impoundments can, and often
does, incorporate a qualitative consideration of the effect of predictable geomorphological and
climatological processes on the integrity of the impoundment system. This could cover periods
of up to 10 000 years, but is typically 200–1000 years. This is referred to as the long term
period. Largely owing to geomorphological processes within such periods, even the most
soundly engineered impoundment system cannot be expected to ensure complete retention of
the tailings material. In certain circumstances, however, natural changes may even produce
improved confinement of wastes rather than deterioration. The choice of an engineering
design life for structures is made with the realization that there can be no certainty in our
knowledge or expectation of what may happen after many years in the future. Nevertheless,
when making assessments of alternative options for the disposal of tailings, we should also
be concerned with what might happen after a time beyond the design life. Thus, while we
might assume that a well designed above ground impoundment will provide reasonable isolation
for 1000 years, or even more, below ground disposal should provide a much longer period
of isolation."

100
The EPA in 40 CFR 192.02 requires that control of tailings be designed to be effective for 1000 years, to the extent reasonably achievable, but at least 200 years in any case.

The Guidelines to the Australian Waste Code call for the design life of the containment structure (performance to be fully in accordance with design objectives) to be at least 200 years and the structural life (during which time the structure must continue to perform its basic functions, possibly at a reduced level) to be of the order of 1000 years.

There might appear to be an inconsistency in the IAEA recommendation that the structure be unaffected by natural processes for up to 10 000 years and the Australian and US requirements of guaranteed performance for 200 years together with expected structural integrity for 1000 years. In reality, there is no inconsistency; the longer term life of a tailings impoundment is desirable but the shorter term requirements recognize the practical limits on our knowledge of the future. This limitation is also recognized in the Canadian recommendation, which suggests that modelling of impacts need not exceed the 10 000 year term.

A hidden issue in the design of containments for long term tailings disposal is the assumption that the factors affecting impoundment integrity are uniform in time. The important issue to be addressed in considering the integrity of tailings containment structures is not whether impoundments can be constructed to last for 200 or 1000 years, but the probability of failure of the structure during these periods. When there is an annual possibility of more than one event affecting the integrity of a tailings impoundment, and the occurrence of events exceeding any specified value is treated as a Poisson arrival process, then the relationship between the probability $P$ of one or more exceedances of design capacity during a specified design life $L$ of a structure whose design has an event recurrence interval $Y$ is expressed by the equation

$$P = 1 - e^{(-L/Y)}$$

In an environment where the probabilistic factors can be expected to have a significant impact upon the integrity of a tailings impoundment, it is unrealistic to require an engineered structure to perform absolutely to its design specifications over its full design life. Engineering reality would require the specification of a limit on the probability of failure. For example, the containment structure might be required to be designed to a 200 year ‘design life’, with a probability of failure of no greater than 2%. To achieve this, the impoundment would need to be designed to withstand not only normal wear and tear, but extreme events with a recurrence probability of no more than once in 10 000 years.

The 200–1000 year period should be considered as one where the target remains containment of tailings; however, some loss in effectiveness of the containment might occur and an increasing probability of failure of the containment may
have to be accepted. In this time-frame, it would not be unreasonable to accept that some remedial/maintenance action could be taken. The design objective for containment is appropriately described by specifying an acceptable limit on the probability of failure at the end of the structure life period. If a 10% probability of some exposure of tailings after 1000 years is accepted as a reasonable limit, the design criterion would require that the structure be able to withstand extreme events with a recurrence probability of no more than once in 10 000 years.

With this background, it is possible to formulate guidelines that could be considered appropriate for modelling the performance of a tailings containment over three future time periods:

(a) 0–200 years, during which time there will be no release of tailings (with a probability of, say, 98%) and the tailings containment must perform in all respects to design specifications.

(b) 200–1000 years, during which time the impoundment structures might degrade to some degree but the tailings solids will be contained totally (with the probability of tailings exposure no more than, say, 10% in 1000 years).

(c) The post-1000 year period, in which the tailings containment will continue to degrade and it is possible that tailings will eventually be released to the environment. Evaluating the impact (detriment per year) will require modelling of the rate of release of the tailings and their dispersion into relevant components of the environment. It would not be useful to extend the time-scale for such modelling beyond the point at which significant differences between containment options can be indicated, almost certainly not beyond 10 000 years.
Annex VI

NATIONAL EXPERIENCE IN THE DECOMMISSIONING/CLOSEOUT OF FACILITIES AND RESIDUES FROM THE MINING AND MILLING OF RADIOACTIVE ORES

Australia
Canada
China
France
Germany
Slovenia
Spain
USA
AUSTRALIA

This section describes the decommissioning/closeout of the Rum Jungle uranium-copper open cut mine and mill in Australia. The site was mined at a time when the environmental and occupational health standards governing mining activities were less stringent than they are now and mining was carried out without planning for decommissioning/closeout. The principle aim of the cleanup described here was to reduce the public health hazard and the environmental effects associated with the site. The decommissioning/closeout details do not necessarily reflect what would be required in Australia today.

Rum Jungle is an abandoned mine that operated between 1954 and 1971, producing uranium, copper, nickel and lead. In 1977, an initial cleanup was carried out by the Australian Government. This involved removal of debris associated with mining and milling activities and was aimed at improving the safety of the site rather than reducing the generation of pollutants on-site. Effluent from the treatment plant and leachate from the mine wastes had resulted in severe environmental degradation of the Finniss River system, the east branch of which flows through the site, and its surroundings. A 4 year programme of rehabilitation commenced in 1982. Plans of the site before and after rehabilitation are provided in Figs A-1 and A-2, respectively.

(1) LOCATION AND OWNERSHIP

The Rum Jungle mine and mill are located in the Northern Territory in Australia at a latitude of 13°0' South and a longitude of 130°59' East. The Rum Jungle mine and mill complex was operated by Territory Enterprises Pty Ltd, a subsidiary of Consolidated Zinc Pty Ltd (now known as CRA Pty Ltd), as agent for the Australian Government.

(2) CLIMATIC CONDITIONS

(a) Precipitation: The climate is monsoonal, with a wet summer season lasting from November to April. Rainfall is strongly seasonal and highly variable. High intensity rainfall occurs during thunderstorm activity in the early wet season (January to March). Generally, little rain falls in the dry season. The mean annual rainfall is 1600 mm, 90% of which is received between November and March.

(b) Temperature: There are high average temperatures throughout the year and high evaporation rates.
FIG. A-1. Rum Jungle site plan before rehabilitation.
(c) **Wind:** The prevailing wind during the dry season is southeasterly at less than 16 km/h. During the wet season the wind is north-northwesterly.

(3) **DEMOGRAPHICS**

The major town in the region, Darwin (population 73,000), is 65 km north of the site. Rum Jungle is located near the small township of Batchelor (population 630). The population in the surrounding area is low.

(4) **GEOLOGY AND TOPOGRAPHY**

The Rum Jungle area is a mature peneplain. The height above sea level is less than 60 m and the relief is 15–30 m in the main catchment areas. Topographically, the area is gently undulating, with a creek system through and around the site. The site is located on the western side of the Pine Creek geosyncline, where Early Proterozoic metasediments are unconformably draped around two Archaean granitic basement complexes. Uranium and base metal mineralization occur in graphitic or chlorotic, pyritic phyllite of the Whites Formation at its contact with the underlying dolomite–magnesite of the Coomalie Dolomite. The Coomalie Dolomite is characterized by a deep weathered profile that exhibits large variations in the depth of weathering. Where the dolomite is weathered and cracked, it is prone to solution channelling and acid attack; in these zones, the permeability is unpredictable and generally very high. Such weathered dolomite is characterized by solution channels, sink holes, cavities and even large caverns. Sink holes have been reported in the area.

(5) **HYDROGEOLOGY AND HYDROLOGY**

The principal streams in the area are the east branch of the Finniss River and Fitch Creek. The east branch of the Finniss River is an important tributary of the Finniss River system (see Fig. A–3).

(6) **MISCELLANEOUS SITE PROBLEMS AND OBJECTIVES**

Not applicable.

(7) **MINE**

(a) **Type/size:** The mine is a uranium–copper open cut mine. Ore for treatment at Rum Jungle was extracted principally from five open cut mines: Whites Open Cut,
Dysons Open Cut, Intermediate Open Cut (copper only), Rum Jungle Creek South and Mount Burton Open Cut. The latter two mines, located some distance from the treatment site, were not judged to be significant contributors to the pollution of the Finniss River system and, hence, were not included in this rehabilitation programme. The Whites and Intermediate Open Cuts, which had become polluted as a result of acid mine drainage, were hazardous to human health and were contributing significantly to pollution of the Finniss River. Dysons Open Cut contained a relatively
small amount of water. The Whites, Dysons and Intermediate Open Cuts cover a total area of 22 ha; 3500 t of uranium oxide and 20 000 t of copper concentrate were processed on-site at Rum Jungle. The depth and volume are shown below.

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (m)</th>
<th>Volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whites</td>
<td>105</td>
<td>3 500 000</td>
</tr>
<tr>
<td>Dysons</td>
<td>45.7</td>
<td>920 000</td>
</tr>
<tr>
<td>Intermediate</td>
<td>70</td>
<td>970 000</td>
</tr>
</tbody>
</table>

(b) **Ore grade:** 0.23–0.35% $\text{U}_2\text{O}_8$.

(c) **Method of decommissioning**

(i) *Dysons Open Cut*: Water in the open cut was drained and released into the local rivers. Haul roads were constructed from the cut to the tailings area. The cut was filled with tailings that were intermixed with copper heap leach pile material above the water table and with affected soils taken from below the copper heap leach pile. The surface of transported materials was shaped to suit the surrounding contours and over this impervious clay covers were constructed that included scour resistant structures and drainage channels. Soil and anti-scour were placed over these impervious covers, the haul roads removed and the area revegetated.

(ii) *Intermediate Open Cut*: Water in the open cut contained less pollutants than that in the Whites Open Cut. It was treated in situ by direct addition of hydrated lime, which encouraged the heavy metals to precipitate and settle to the pit floor; the accumulated sludge was then removed. Disposal of the filter cake was by burial in a borrow pit area.

(iii) *Whites Open Cut*: Water in the open cut was treated using the treatment plant, following which crushed limestone was placed in the pit to assist with long term water quality stability. Whites Open Cut was connected by a channel to the Intermediate Open Cut. The haul roads were removed, the borrow pits filled and the area landscaped and revegetated.
(d) **Cost of decommissioning:** This is shown below.

<table>
<thead>
<tr>
<th>Site</th>
<th>Total expenditure to 30 June 1986 (A $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dysons (earthworks)</td>
<td>8 098</td>
</tr>
<tr>
<td>Whites (earthworks)</td>
<td>320 268</td>
</tr>
<tr>
<td>Intermediate (earthworks)</td>
<td>240</td>
</tr>
<tr>
<td>Treatment plant (construction)</td>
<td>2 016 228</td>
</tr>
<tr>
<td>(operation)</td>
<td>1 392 400</td>
</tr>
</tbody>
</table>

(e) **Surface and groundwater controls:** A hydroxide precipitation water treatment plant was constructed for the in situ treatment of water with lime in the Whites and Intermediate Open Cuts to neutralize and precipitate the heavy metals. On completion of the treatment of both these open cuts, the east branch of the Finniss River was diverted into the Whites Open Cut, leaving the connection channel between the Whites and Intermediate Open Cuts as a permanent feature. A system of weirs was used to improve the water quality naturally in the pits with time by mixing with and flushing of the in situ waters.

(f) **Monitoring and institutional control requirements**

(i) **Whites and Intermediate Open Cuts:** Monitoring of the water quality and temperature profiles in both these open cuts and measurement of the groundwater levels and quality in adjacent monitoring bores are to continue. Revegetation of embankments is also being monitored.

(ii) **Dysons Open Cut:** Monitoring of the local groundwater regime around the open cut is continuing to confirm containment of the tailings material. The condition of vegetation and erosion covers and drains and the settlement of fill in the open cut are also being monitored. Following any release of water from the open cut pits, the water quality of the Finniss River downstream of its confluence with the east branch is measured to determine whether it meets the criteria recommended by the Australian National Health and Medical Research Council for drinking water. Groundwater at the water treatment plant filter cake disposal site is being monitored (see also items (13) and 14)).

110
(8) MILL

(a) **Type/size:** The uranium treatment plant and ore stockpile area is 45 ha in size.

(b) **Grade milled:** 0.23–0.35% U$_3$O$_8$.

(c) **Method of decommissioning**

(i) **Immediate:** The area was partially rehabilitated in 1977 after the closure of the mine. This involved using the below grade ore stockpiles as fill material over the area previously occupied by the plant and coverage with a layer of topsoil and revegetation. These measures, although achieving some level of site safety, did not remove the pollution sources.

(ii) **Long term:** The measures carried out as part of the 1983–1986 rehabilitation programme included treatment of the acidic surface material with lime, and establishment of the surface and groundwater control measures described below. Owing to the toxicity of the underlying material, an impervious clay cover was placed over the area. The site was revegetated.

(d) **Cost of decommissioning:** This is unknown.

(e) **Surface and groundwater controls:** The rehabilitation programme included contouring of the site to facilitate drainage, construction of erosion control banks and drains, and sealing of the area with an impermeable clay cover to prevent infiltration of rain water and leaching of contaminants.

(f) **Monitoring and institutional control requirements:** Erosion and the condition of covers and vegetation are being monitored (see also items (13) and (14)).

(9) TAILINGS IMPOUNDMENT(S) AND WASTE TREATMENT FACILITIES

(a) **Type of impoundment**

(i) **Mine-pit impoundment:** Both the Whites and Dysons Open Cuts were used as tailings disposal sites during the operation of the mine.

(ii) **Dam impoundment:** Some of the wastes from the ore treatment process were discharged into an area known as the Old Tailings Dam.
(b) **Quantity and surface area:** The Old Tailings Dam disposal site contained about $0.6 \times 10^6$ t of tailings and covered an area of 31 ha. The average depth of the tailings was about 1 m, with maximum depths of 2–3 m.

(c) **Activity and physical characteristics:** These tailings consisted of finely ground acid leached waste from processed ore. The tailings material contained the daughter products of the uranium decay series and was a low level source of radioactivity.

(d) **Non-radiological contaminants:** The tailings wastes were acidic and contained significant concentrations of heavy metals, including zinc, manganese and particularly copper.

(e) **Method of decommissioning:** At the Old Tailings Dam tailings, together with affected subsoil, were removed and placed on top of existing tailings in the Dysons Open Cut, where they were covered with material from the copper heap leach pile, sealed and vegetated. After removal of the tailings and subsoil, lime was used to treat the acidic areas, topsoil was spread, drainage constructed and the area revegetated.

(f) **Cover characteristics:** A rock blanket of 1 m constructed on a geotextile fabric layer was placed over the tailings. On top of this, other fill material was placed, followed by an impervious clay cover.

(g) **Cost of decommissioning:** The total cost of earthworks required in the rehabilitation of the tailings dam up to 1986 was A $138 157.

(h) **Surface and groundwater controls:** Dysons Open Cut is a geomorphologically stable site above any potential groundwater influence allowing for permanent containment of the tailings. A rock blanket placed over the tailings provided a drainage path for any pore water released from the tailings during consolidation. This was connected to the subsoil drainage system. To intercept any groundwater entering the fill material from the high side of the open cut, the rock blanket was extended up the face of the original open cut and above the level of the tailings. The tailings area was not a major contributor to the annual pollutant load entering the east branch of the Finniss River. The area was reshaped to form watercourses and to minimize infiltration. Rock and other protection bunds in the tailings area were placed strategically to control scouring and erosion.

(i) **Monitoring and institutional control requirements:** The migration of radium in the subsoil was monitored as part of the initial monitoring programme. Monitoring of the revegetation and erosion of the area is continuing as part of a reduced monitoring programme (see also items (13) and (14)).
MINING DEBRIS PILES

(a) **Type of pile:** Surface overburden (waste rock) heaps — the three overburden heaps were known as Whites (including Whites North), Intermediate and Dysons.

(b) **Quantity and surface area:** The three overburden heaps contained a total of $10 \times 10^6$ t of material and covered an area of some 50 ha (see below).

<table>
<thead>
<tr>
<th>Site</th>
<th>Area (ha)</th>
<th>Volume $(m^3 \times 10^6)$</th>
<th>Weight $(t \times 10^6)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whites</td>
<td>26.4</td>
<td>4.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Whites North</td>
<td>4.0</td>
<td>0.32</td>
<td>0.64</td>
</tr>
<tr>
<td>Dysons</td>
<td>8.5</td>
<td>1.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Intermediate</td>
<td>7.0</td>
<td>0.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

(c) **Activity and physical characteristics:** Information not available.

(d) **Non-radiological contaminants:** The overburden heaps contained about 5% pyrite and iron sulphide mineral that was oxidizing chemically and bacteriologically to produce acid mine drainage containing sulphuric acid and high levels of iron, copper, zinc, cobalt and nickel.

(e) **Method of decommissioning:** The Whites North overburden heap was removed to the Whites overburden heap, and the area it had occupied was landscaped and revegetated. The heaps were contoured, covered and revegetated. Acidic soils were removed from the surrounding areas, and the surfaces treated with lime and revegetated where necessary.

(f) **Cover characteristics:** Impervious compacted clay covers were used to prevent air and water entering the piles. The cover system comprised a low permeability sealing zone, a moisture retention zone and an erosion protection zone. Over this cover, topsoil and anti-scour were placed and the area revegetated.
(g) **Cost of decommissioning:** This is shown below.

<table>
<thead>
<tr>
<th>Site</th>
<th>Total expenditure to 30 June 1986 (A $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dysons</td>
<td>262,047</td>
</tr>
<tr>
<td>Whites</td>
<td>1,376,783</td>
</tr>
<tr>
<td>Intermediate</td>
<td>491,396</td>
</tr>
<tr>
<td>Whites North</td>
<td>696,771</td>
</tr>
</tbody>
</table>

(h) **Surface and groundwater controls:** Together, the heaps constituted the most serious source of pollution entering the Finniss River system. The heaps were contourd, erosion protection structures constructed and the area revegetated. The diversion channel between the Whites and Intermediate heaps was reshaped to form a natural watercourse to allow passage of any excess water in high rainfall periods.

(i) **Monitoring and institutional control requirements**

   (i) **Dysons overburden heap:** Erosion of covers and drains and the condition of vegetation are being monitored.

   (ii) **Whites and Intermediate overburden heaps:** Monitoring of the water balance rainfall infiltration rates and the chemical activity of the Whites and Intermediate overburden heaps is to continue until long term trends have been established. Monitoring of groundwater in and around the heaps involves monitoring of the water levels and the quality of the aquifer system. Chemical activity studies include measurement of the oxygen, moisture content and temperature within the heaps. Monitoring of the erosion covers and drains and the condition of vegetation on the heaps is being carried out.

   (iii) **Area of former Whites North overburden heap:** Erosion of the area and the condition of vegetation are being monitored (see also items (13) and (14)).

(11) **HEAP LEACH PILES**

(a) **Type of pile:** The copper heap leach pile was constructed from low grade copper ore mined from the Intermediate Open Cut as an experiment aimed at extracting
copper by acid leaching. The extraction process involved the use of launders and ponds. The experiment was unsuccessful, and large amounts of copper remaining in the pile had been released slowly into the environment by both chemical and biological oxidation. The impervious layer at the base of the heap and ponds had broken down and the area was saturated with acid mine drainage.

(b) **Quantity and surface area:** The pile contained about $0.37 \times 10^6$ t of low grade copper ore and covered an area of about 2 ha.

(c) **Activity and physical characteristics:** Information not available.

(d) **Non-radiological contaminants:** Heavy metals and acid.

(e) **Method of decommissioning:** The heap leach pile, together with contaminated subsoil, copper launders, ponds, and associated concrete pads and footings, were removed and placed in the Dysons Open Cut on top of the rock blanket covering the tailings. The area was then sealed, reshaped and revegetated.

(f) **Cover characteristics:** Impervious compacted clay covers were used to prevent air and water entering the piles. The cover system comprised a low permeability sealing zone, a moisture retention zone and an erosion protection zone. Over this cover, topsoil and anti-scour were placed and the area revegetated.

(g) **Cost of decommissioning:** The total cost of earthworks required in the rehabilitation of the copper heap leach pile up to 1986 was A $3 539 670.

(h) **Surface and groundwater controls:** Dysons Open Cut is a geomorphologically stable site above any potential groundwater influence allowing for permanent containment of the ore. After removal of the heap leach pile, contaminated subsoil and structures, the remaining area was deep ripped to promote natural drainage of the soil and reshaped to drain surface water towards Copper Creek. A subsoil drainage system was designed to encourage leaching of the contaminated subsoil.

(i) **Monitoring and institutional control requirements:** Revegetation and erosion of the area are being monitored (see also items (13) and (14)).

(12) **VICINITY PROPERTY REMEDIATION**

(a) **Type of remediation:** The aim of the rehabilitation programme was to restore the area to a standard compatible with recreational use, although some specific restrictions will need to be applied in some areas.
(b) **Removal or cover of material:** Small ore stockpiles scattered around the Rum Jungle site were removed and buried in costeans around the site. Local creekbeds, contaminated ponds, old roads and the general surroundings were cleaned up and revegetated where necessary. A stock fence was erected around the perimeter of the site before revegetation commenced to exclude feral buffalo. The Acid Dam was used as part of the waste retention system for the uranium treatment plant and the Sweetwater Dam was affected by outwash of acid mine drainage from the Whites overburden heap. The dam walls were removed and the river beds flushed. All the affected river banks were ripped and treated with lime and allowed to revegetate naturally. Flood and erosion protection structures were constructed along the stream to control water during the wet season.

(c) **Cost:** The total cost of earthworks required in the rehabilitation of the Acid and Sweetwater Dams up to 1986 was A $ 204,231.

(d) **Monitoring**

(i) **Acid and Sweetwater Dams:** The condition of the stream bed and embankment is being monitored.

(ii) **Regional:** The height and quality of groundwater have been monitored since commencement of the rehabilitation programme to establish the pathways of pollution transport and the time-scale for improvement of water quality; this is expected to continue for at least another 5 years. Monitoring of surface water quality in the Finniss River, its east branch and the open cut pits is continuing to safeguard the water resource of the Finniss River system. This has included monitoring the rainfall, runoff, annual flow and river water quality. A radiation survey to confirm the long term radiological safety of the Finniss River system has been carried out. Stream bed sediments of the east branch of the Finniss River are also being monitored. A flora and fauna survey is to be carried out to establish the effects of the rehabilitation programme on the flora and fauna of the Finniss River system. Monitoring of the revegetation process as well as the condition of vegetation on the revegetated sites and the erosion of the area will continue.

(13) **MONITORING**

A monitoring programme was established as an integral part of the rehabilitation project to determine the effectiveness of rehabilitation measures. The programme commenced prior to rehabilitation action and continued throughout the work and for 2 years after completion of the rehabilitation. On the basis of a review of the monitoring programme and its results, it was decided that a reduced
programme of monitoring and maintenance would be required to ensure the continued integrity of the measures. Site and water quality monitoring will continue until the project objectives are met and the long term trends established. The maintenance programme involves erosion control, revegetation, maintenance of firebreaks, fences and rediversion work, as well as weed and feral animal control.

(14) INSTITUTIONAL CONTROL REQUIREMENTS

The long term effectiveness of rehabilitation measures depends on the integrity of the work; use of the area is restricted to ensure that activities do not occur which may compromise their integrity. The area has been declared a 'Restricted Use Area' under State legislation and all activities on-site are closely supervised. The site is not suitable for permanent habitation.

(15) TOTAL COST OF REHABILITATION

The total cost of the 4 year rehabilitation programme completed in 1986 was A $18.6 \times 10^6$. Ongoing monitoring and maintenance costs are being incurred.
CANADA

Three separate uranium mine/mill facilities are undergoing decommissioning in Canada, namely, Beaverlodge, Madawaska Mines and Agnew Lake. The regulatory approach has been described elsewhere\(^2^4\). Factors related to the decommissioning/closeout of the Beaverlodge facility are reported below.

(1) LOCATION AND OWNERSHIP

The Beaverlodge mining and mill operations were operated originally by Eldorado Resources Limited, now called Cameco. The site is located on the north shore of Lake Athabasca in the extreme northwest corner of the Province of Saskatchewan, Canada. Intensive exploration began in 1944. Ore was mined from 1950 to 1982. Milling operations began in 1953 and continued until June 1982. Beaverlodge is located at a latitude of 59°34' North and a longitude of 108°0' West.

(2) CLIMATIC CONDITIONS

The climate is of the northern Canadian continental type found on the southern edge of the northwestern transition section of the boreal forest region. Summers are normally warm for the latitude, but winters are usually long and intensely cold under the influence of the cold Arctic air masses.

(a) Precipitation: The climate is fairly dry, with a mean annual precipitation of 354.2 mm; the maximum 24 hour rainfall and snowfall are 38.4 mm and 47 cm, respectively.

(b) Temperature: The mean annual temperature is \(-3.7^\circ\text{C}\), with a maximum of \(34.4^\circ\text{C}\) and a minimum of \(-48.9^\circ\text{C}\).

(c) Wind: The wind is predominantly easterly, averaging 8 km/h in winter and 12 km/h in summer.

\(^{2^4}\text{ATOMIC ENERGY CONTROL BOARD, Decommission of Uranium Mines and Mills — Canadian Regulatory Approach and Experience, Rep. INFO-0219, AECB, Ottawa, ON (Sep. 1986).}\)
(3) DEMOGRAPHICS

There are two main communities associated with Beaverlodge and the other nearby mining facilities. Adjacent to the mill site was the company owned Beaverlodge town site, which was used exclusively for housing company employees. The main centre was Uranium City, which is located 8 km west of the mill. This city was founded by the Provincial Government in 1953. By 1982, the town’s population had declined to 3000 inhabitants. Following the 1981 announcement that the Beaverlodge mine/mill operations would be shut down, the population declined rapidly; as of the end of 1991, approximately 195 people live in the Uranium City area.

(4) GEOLOGY AND TOPOGRAPHY

The geology of the Beaverlodge area is typical Precambrian Shield having a rugged rock knob complex, 60% of which is rock outcrop. The depressions have filled with water, forming many lakes, streams and muskeg swamps. The sheet like ground moraine cover is only a few centimetres thick on some outcrops and up to tens of metres thick in some depressions. There is no arable land in the area. The area is located in the Canadian Shield physiographical region and has been tectonically inactive for millions of years. The rocks are of Precambrian age, specifically of the Archaean and Aphebian eras. The main groups of rock consist of a variety of metamorphic rocks, metasomatic granite and gneissic rocks, plus sedimentary and volcanic rocks.

(5) HYDROGEOLOGY AND HYDROLOGY

Owing to the typical tight rock formations, very little groundwater flow occurs in the region. The hydrology consists of two main watersheds, the Ace Creek system (153.6 km$^2$) and the Lake Fookes system (14.1 km$^2$), both of which flow to Lake Beaverlodge and then to Lake Athabasca. The drainage systems are poorly developed and in some sections highly disorganized. Flows are normally from lake to lake through fast flowing creeks and swamps. The annual unit runoff rate was modelled with 0.97 and 0.53 L·s$^{-1}$·km$^{-2}$, respectively, for the two basins.

(6) MISCELLANEOUS SITE PROBLEMS AND OBJECTIVES

The overall decommissioning costs were calculated at Can $13 \times 10^6$ in 1983 money values. An area by area breakdown was not available. The main objec-
atives/requirements established by the regulatory agencies, in co-operation with the company, were:

(a) Gamma fields measured at a height of 1 m should not exceed 250 $\mu$R/h, but the objective would be a reduction to <250 $\mu$R/h in accordance with the ALARA principle

(b) Approved procedures shall be followed for the decontamination or disposal of equipment; equipment for salvage will be decontaminated such that the alpha emitting radionuclides are reduced to 3.7 kBq/m$^2$ on the surface

(c) The water quality objectives applicable for closeout at the four principal locations were: uranium: 0.25 mg/L; total $^{226}$Ra: 0.11 Bq/L; total dissolved solids: 250 mg/L; pH: 6.5–9.5; total suspended solids: background + 10 mg/L; copper: 0.02 mg/L; zinc: 0.05 mg/L; arsenic: 0.01 mg/L; iron: 0.3 mg/L; and lead: 0.05 mg/L.

(7) MINE

(a) Type/size: About 10 161 389 t of ore were recovered from the 17 different mining areas associated with the Beaverlodge complex. The main underground operation was accessed by the shafts at Fay, Verna and Ace. Four other ore bodies were also underground operations: Hab, Dubyna, 72 Zone and Lake Martin. In addition, 12 open pit mines operated around the Beaverlodge site.

(b) Ore grade: The average ore grade for the 17 sites was 0.25%. The overall average grade per site ranged between 0.10 and 0.43%.

(c) Method of decommissioning: In early 1982, the sealing of 35 vertical and 10 horizontal openings began. The horizontal openings were backfilled with 17 m of waste rock and the vertical openings sealed with reinforced concrete. The open pit mines were backfilled and the site graded, including the waste rock piles. All surface structures were removed and any adits backfilled. The mine shafts and vent raises of the Fay–Verna underground complex were also used for the disposal of various waste materials (i.e. mine/mill sludges).

(d) Cost of decommissioning: No separate costs are available for the decommissioning of mines (see total costs in item (6)).

(e) Surface and groundwater controls: Areas were closed out and the sites contoured to shed runoff. Inflows to and from the mine workings are difficult to find or monitor.
(f) **Monitoring and institutional control requirements:** Annual inspections of the main mine areas are continuing. The licensee, Cameco, currently retains a decommissioning licence with the AECB (AECB-MFDL-340-0) but has not filed for an abandonment approval. Ultimately, the lands will be returned to the Province of Saskatchewan for institutional control.

(8) **MILL**

(a) **Type/size:** In 1953, the mill began using an alkaline pressure leaching system at a rate of 454 t/d. Changes to the mill were made and, in 1957, an expanded mill capacity of 1800 t/d was achieved using an atmospheric leach process, with a pyrite flotation and an acid leaching circuit. The Beaverlodge mill was the only carbonate leaching uranium mill in Canada.

(b) **Grade milled:** The overall mill rate averaged 0.25%. In total, 9,991,369 t of ore was milled, producing 20,671,883 kg of yellow cake. The ore contained very little thorium, averaging only 15 ppm.

(c) **Method of decommissioning:** Following decontamination and salvage of mill equipment and materials, the structures and unsalvageable materials were demolished, the voids filled with waste rock, and the area covered and contoured with a total of 259,100 m$^3$ of waste rock. Some small areas of slumping and collapse required additional cover.

(d) **Cost of decommissioning:** No separate costs are available for the decommissioning of the mill (see total costs in item (6)).

(e) **Surface and groundwater controls:** The mill is located on a topographical high and all runoff flows to Ace Creek. Monitoring of Ace Creek continues on a monthly basis, with costs jointly shared by Cameco and the Provincial Government.

(f) **Monitoring and institutional control requirements:** Annual inspections of the mill area are continuing. See (f) in item (7).

(9) **TAILINGS IMPOUNDMENT(S) AND WASTE TREATMENT FACILITIES**

(a) **Type of impoundment:** The main tailings area is called Lake Fookes. Starting in 1957, tailings were discharged via pipeline into the upper reaches of the lake. Tailings were also deposited in Lake Minewater (1953) and Lake Marie (1954–1957).
The water level control structures were constructed at the Lakes Fookes and Marie outlets in 1969 and 1971, respectively. In addition, numerous tailings spills occurred over the 30 year operating life, with tailings solids covering 23.3 ha adjacent to Ace Creek and the tailings line corridor to Lake Fookes. The Meadow Dam was constructed in 1977, and the overflow water from Lakes Fookes and Marie drained through the Lake Meadow treatment system. The final effluent was discharged into Lake Beaverlodge via Lake Greer. Barium chloride was added at the headwaters of Lake Meadow for the settling of particulate and precipitated radium, producing a radium–barium–sulphate precipitate. Lake Minewater was used for settling radium sludges from the treated mine water between 1971 and 1982, but from 1953 to 1971 it received mine slimes and sanitary wastes from underground. Lake Minewater also drains into Lake Meadow.

(b) **Quantity and surface area:** Over the 30 year operating life, $10.1 \times 10^6$ t of tailings were produced. Approximately $5.8 \times 10^6$ t remained on the surface in the above lake basins, the remainder being used for mine backfill, i.e. cycloned. Including the downstream Lake Meadow treatment area, the tailings system area covers approximately 1.1 km$^2$. The majority of the tailings were deposited below the lake water level. For example, only 7% (9.2 ha) of the Lake Fookes surface area consisted of exposed tailings.

(c) **Activity and physical characteristics:** 42.5% of the mill tailings were cycloned and placed as backfill underground. The remaining volume was discharged in the surface tailings/lake system. However, most of the total radium (about 80%) was contained in the $-200$ mesh fraction, thus concentrating in the slime fraction discharged to Lake Fookes. Exposed tailings (above water) exhibited gamma levels of up to 1200 $\mu$R/h at a height of 1 m. During the later stages of operation, the effluent discharge of uranium and $^{226}\text{Ra}$ averaged 4.0 mg/L and 3.0 Bq/L, respectively, at the Lake Fookes outlet; 3.5 mg/L and 0.6 Bq/L, respectively, at the Lake Marie outlet; and 3.8 mg/L and 0.15 Bq/L, respectively, at the Lake Meadow outlet.

(d) **Non-radiological contaminants:** Non-radiological contaminants include major ions, sulphates and chlorides and other heavy metal contaminants, e.g. copper, arsenic, nickel, lead and zinc were low in concentration.

(e) **Method of decommissioning**

(i) **Lake Fookes:** Hydraulic management was chosen for the overall control of the tailings and waste treatment areas. The Lake Fookes water level was lowered initially to expose more tailings, and 600 mm of waste rock cover (88540 m$^3$) were placed on 10.5 ha of exposed tailings. The gamma levels were reduced to 250 $\mu$R/h
(or less) at 1 m. The lake level then recovered about 1 m, and the natural outlet was controlled/reinforced with coarse rock riprap and shotcrete.

(ii) **Lake Marie:** Following temporary lowering of the lake, 80% of Lake Marie's tailings (76 110 m$^3$) were relocated in the deep section of the lake, and 29 110 m$^3$ of waste rock were used to cover the remaining exposed tailings beaches (~5% of the lake's surface area). The gamma levels were reduced to 250 μR/h (or less) at 1 m. The lake's natural outlet was reinforced in a manner similar to Lake Fookes.

(iii) **Lake Meadow:** The lake was also lowered via the control structure, and 6 470 m$^3$ of treatment sludges were excavated and placed in the Ace vent raise. The sludge thickness varied between 10 and 100 mm, averaging 20 mm. The lake basin was allowed to recover naturally and the control dam outlet left open. A small channel flows through the centre of the basin, draining the Lakes Fookes and Marie waters and the small drainage from the Lake Minewater area.

(iv) **Lake Minewater:** Tailings and treatment sludges (119 250 m$^3$) were excavated and deposited down the Ace vent raise. The basin was recontoured and a small wetlands area has developed.

(f) **Cover characteristics:** See (e) in item (9).

(g) **Cost of decommissioning:** No separate costs are available for the decommissioning of the tailings (see total costs in item (6)).

(h) **Surface and groundwater controls:** Lakes Fookes and Marie have been reverted back to pre-operational water levels, with the natural outlets controlled/reinforced with coarse rock riprap and shotcrete. Lake Minewater was drained significantly via a ditch, and a small wetlands area remains. The Lake Meadow concrete dam was not removed, but the stop logs have been removed. A channel flows through the centre of the basin, and the remaining Meadow Basin has been regrown with cattails and wetland grasses. Owing to the tight nature of the rock, the groundwater regime was considered minimal in the total water balance. No controls exist for the groundwater.

(i) **Monitoring and institutional control requirements:** The effluent treatment system was shut down in 1986. Water quality monitoring of the lakes' outlets continues and, as of summer 1991, monitoring of Lakes Fookes, Marie and Meadow has revealed the following levels of uranium and $^{226}$Ra: 2.24 mg/L and 0.64 Bq/L, respectively, at the Lake Fookes outlet; 2.13 mg/L and 0.98 Bq/L, respectively, at the Lake Marie outlet; and 1.94 mg/L and 0.67 Bq/L, respectively, at the Lake
Meadow outlet. Surveys/inspections of the covered tailings continue annually. Some minor remedial work is planned to re-establish cover on any exposed tailings and to maintain the gamma fields at <250 $\mu$R/h.

(10) MINING DEBRIS PILES

(a) **Type of pile:** Mine waste rock.

(b) **Quantity and surface area:** There were 13 storage areas developed for the mining debris. This resulted in approximately $4.8 \times 10^6$ t (or $3 \times 10^6$ m$^3$) of mining debris covering 55.8 ha.

(c) **Activity and physical characteristics:** The uranium content varied from 0.002 to 0.062%. The gamma levels averaged 86 $\mu$R/h (the range was 60–104 $\mu$R/h).

(d) **Non-radiological contaminants:** There were no significant chemical or other contaminants. The waste was primarily made up of silicon and aluminium oxides, with small amounts of iron and calcium oxides and sulphate. No acid generating mining debris has occurred.

(e) **Method of decommissioning:** No cover or disposal of mining debris was required because of the high natural gamma radiation fields in the vicinity and the low levels exhibited by the mining debris. The rock was used for backfill of openings, pits and tailings cover, etc. Some resloping of the waste piles was also undertaken for stability and aesthetic reasons.

(f) **Cover characteristics:** Resloping was the only general requirement. No revegetation or reseeding programmes were initiated because generally the area is made up of 60% exposed bedrock.

(g) **Cost of decommissioning:** No separate costs are available for the decommissioning of the mining debris (see total costs in item (6)).

(h) **Surface and groundwater controls:** None.

(11) HEAP LEACH PILES

There are no heap leach piles at the Beaverlodge site.
The company's adjacent Beaverlodge town site was demolished, since no purchaser could be found. Some materials were salvaged, and the remainder buried and then covered. The site was cleaned up, thus removing any future liabilities against the company. During operation of the mine/mill facility in the late 1970s, remedial work was performed in Uranium City. This consisted of removal or covering of the mining debris used as driveway material and of ventilation of the homes that exhibited radon daughter levels exceeding 0.02 WL. No separate costs are available for remediation of the Beaverlodge town site (see total costs in item (6)). The cost to remediate the Uranium City properties was approximately Can $1 000 000. There is no requirement for ongoing monitoring of the vicinity property remediation.
The following is a report on the decommissioning and closeout of mine/mill facility No. 713 in China.

(1) LOCATION AND OWNERSHIP

Mine/mill facility No. 713 is a State owned complex located in the Jangxi Province in southwest China. The mine operated from 1962 to 1983. The mill started operation at the end of 1962. Uranium production ceased in 1990. No. 713 is located at a latitude of 28°24' North and a longitude of 117°48' East.

(2) CLIMATIC CONDITIONS

(a) Precipitation: In this district, the average annual precipitation is 2038 mm and there are between 145 and 190 rainy days. During the rainy period (March to June), 62% of the annual precipitation falls. The record rainfall in 1 day is 214.1 mm.

(b) Temperature: The average annual temperature in the area is 17.8°C. The hottest time of the year occurs between May and August, with the highest and average temperatures during this time being 43.3 and 26°C, respectively. During the coldest months (December and January), the lowest and average temperatures are −3.6 and 5°C, respectively.

(c) Wind: The average annual wind speed is 1.64 m/s. The two most prominent directions are north (24.32% of the time) and northeast (15.23%).

(3) DEMOGRAPHICS

About 5 million people live in an 80 km zone around the mine/mill facility. The population density is about 238 inhabitants/km². The population is mainly Han (Chinese).

(4) GEOLOGY AND TOPOGRAPHY

The mine is located at the southeast end of a valley in a hilly region. The northern, eastern and western parts of the site are higher than the southern and south-
western areas. The topography declines from north to south. The East Hill and West Hill consist of limestone. Uranium mineralization occurs at the top of the Yangxin limestone of the Permian period. Another ore bed, located in tuff, is found about 100 km from the mine headquarters.

(5) HYDROGEOLOGY AND HYDROLOGY

The No. 1 brook has been the drainage ditch for mining and milling flows from north to south and southwest and into the Yongle River. No. 2 brook flows from northeast to southeast and into No. 1 brook at No. 6 spring. The Yongle River, which is 5 km long and 8 m wide, has a flow capacity of 0.4 m$^3$/s. It flows into the River Xin, which is part of the water system of Lake Boyang. The surface and groundwaters are both used for farming and household uses.

(6) MISCELLANEOUS SITE PROBLEMS AND OBJECTIVES

One year before decommissioning started, a monitoring campaign was carried out to obtain information on the contaminated mine and to undertake preliminary evaluation of the environment. For habitable buildings, the objective of remedial action will be to achieve an annual average radon decay product concentration (including background) that will not exceed 0.03 WLM and a gamma radiation level that will not exceed the normal background level by more than 20 $\mu$R/h. After closeout, the radon flux over the surface of the pits must be reduced to an average release rate of less than 0.74 Bq$\cdot$m$^{-2}\cdot$s$^{-1}$. Post-closeout monitoring will be carried on for 1–2 years, at the end of which a final environment evaluation will be made.

(7) MINE

(a) Type/size: There are five open pit mines, with a total volume of 740 000 m$^3$ and depths of 50–100 m.

(b) Ore grade: The average ore grade mined is 0.116% uranium. The radon release rates from the open pits range from 0.002 to 10.82 Bq$\cdot$m$^{-2}\cdot$s$^{-1}$, with an average value of 0.912 Bq$\cdot$m$^{-2}\cdot$s$^{-1}$. The gamma radiation rates range from 8 to 300 $\mu$R/h, with an average rate of 112 $\mu$R/h.

(c) Method of decommissioning: Four of the open pits were covered with topsoil and revegetated. The fifth mine was allowed to flood.
(d) **Cost of decommissioning:** The immediate cost of decommissioning is Y 2.65 × 10^6 (renminbi yuan).

(e) **Surface and groundwater controls:** Control facilities were established to prevent surface and groundwaters from flowing into the open pits.

(f) **Monitoring and institutional control requirements:** One year before decommissioning, a monitoring/evaluation programme was carried out to obtain data on the contaminated mine pits and to prepare a preliminary environmental evaluation. After decommissioning, the radon flux over the pit surface was reduced to an average release rate of less than 0.74 Bq·m^{-2}·s^{-1}. After completion of a 1–2 year monitoring programme, a final environmental evaluation of the closed out mines will be made.

(8) **MILL**

(a) **Type/size:** The mill is of the acid leach type. The uranium processing plant and ore stockpile area cover 8.6 ha. The mill operated from 1962 to 1990.

(b) **Grade milled:** 0.072% uranium.

(c) **Method of decommissioning:** All mill structures, equipment and buildings will be sealed and dismantled separately. Some equipment, after being decontaminated to activity levels that are below regulatory concern, will be used in other industries. Equipment that cannot be cleaned up to an acceptable level will be sealed in the mill. Some pipes and other debris will be placed in tailings impoundments.

(d) **Cost of decommissioning:** The immediate cost of decommissioning is Y 0.59 × 10^6.

(e) **Surface and groundwater controls:** Structures will be constructed to prevent surface and groundwaters from flowing into the mill plants.

(f) **Monitoring and institutional control requirements:** See (f) in item (7).

(9) **TAILINGS IMPOUNDMENT(S) AND WASTE TREATMENT FACILITIES**

(a) **Type of impoundment:** The main type is valley dam impoundments. The tailings dams and evaporation ponds are located in two small valleys 1 km from the mill.
(b) **Quantity and surface area:** 2.7 \times 10^6 t of tailings cover a surface area of 320,000 m\(^2\).

(c) **Activity and physical characteristics:** The radon release rates from tailings impoundments range from 0.001 to 7.56 Bq\(\cdot\)m\(^{-2}\)\(\cdot\)s\(^{-1}\), with an average of 1.81 Bq\(\cdot\)m\(^{-2}\)\(\cdot\)s\(^{-1}\). The gamma radiation rates range from 121 to 476 \(\mu\)R/h, with an average rate of 241 \(\mu\)R/h.

(d) **Non-radiological contaminants:** The tailings have some organic solvent, acidic liquor, etc.

(e) **Method of decommissioning:** In situ closeout with an impermeable cover is the method chosen. Surface and groundwater controls and a special ditch for dewatering rainfall are provided to guarantee the safety of the impoundments.

(f) **Cover characteristics:** The cover over the impoundments will consist of separate layers composed of soils, rocks, cobbles and other materials. The cover will be vegetated with easy to grow herbaceous species, bushes and fast growing trees.

(g) **Cost of decommissioning:** The immediate cost of decommissioning is Y 17.2 \times 10^6.

(h) **Monitoring and institutional control requirements:** See (f) in item (7).

(10) **MINING DEBRIS PILES**

(a) **Type of pile:** The main type is surface piles located beside the open pits.

(b) **Quantity and surface area:** There are 2.9 \times 10^6 t of waste rock, with a surface area of 221,000 m\(^2\).

(c) **Activity and physical characteristics:** In the waste rock, there is some low grade ore containing uranium, radium, radon and their daughters. The average radon release rate from the waste rock piles is 0.673 Bq\(\cdot\)m\(^{-2}\)\(\cdot\)s\(^{-1}\). The average gamma radiation rate is 55 \(\mu\)R/h. There are no non-radiological contaminants in these piles.

(d) **Method of decommissioning:** In situ closeout. A series of walls or ditches will be built at the boundaries of the piles to prevent surface and groundwaters from flowing into the piles.
(e) **Cover characteristics:** A 1 m thick layer composed of earth and rock will be placed on the piles if the radon release rate exceeds 0.74 Bq·m⁻²·s⁻¹ or if the gamma radiation rate exceeds 20 μR/h.

(f) **Cost of decommissioning:** The immediate cost of decommissioning is Y 8.66 × 10⁶.

(g) **Monitoring and institutional control requirements:** See (f) in item (7).

(11) **HEAP LEACH PILES**

   None.

(12) **VICINITY PROPERTY REMEDIATION**

   Some remedial work will be done on buildings for subsidiary production; two railway uranium ore bunkers and the associated railway lines; 2 km of highway that was used during the transport of uranium ore; and mud at some points of the Rivers Yongle and Fenglingkou.

   Contaminated material will be removed and buried in the tailings or covered. Some premises will be dismantled and others cleaned up and reused. The crushed contaminated stone on the railway lines (with an average gamma radiation rate of 98 μR/h) will be cleared away and replaced with clean stone. Contaminated sections of the highway (with an average radon release rate of 0.503 Bq·m⁻²·s⁻¹ and a gamma radiation rate of 56 μR/h) near villages will be cleaned up and covered with new material. The contaminated mud and other material from the rivers will be cleared away.

   The immediate cost of the remedial work is Y 3.9 × 10⁶.
The following is a report on the decommissioning and closeout of the uranium mines and mill at Le Cellier, France.

(1) LOCATION AND OWNERSHIP

The mines and mill are located in the southern part of the French central massif at a height of 1180 m near Le Cellier (Lozère, Department 48, France) at a latitude of 44°43'20" North and a longitude of 3°42'10" East. The owner of the mines and mill is Compagnie générale des matières nucléaires (Cogéma).

(2) CLIMATIC CONDITIONS

The area has a mountainous and continental type of climate in winter, with influences of the Mediterranean type in summer.

(a) Precipitation: The mean annual precipitation for the period 1974–1989 was 897 mm, ranging from 1220 mm in 1977 to 598 mm in 1989. Precipitation can be in the form of snow from November to April.

(b) Temperature: The cold season is from November to March, with an average temperature below 0°C (120–150 days a year). The hot season is from June to September, with a mean maximum temperature just above 19°C.

(c) Wind: The wind is mainly from the northwest and south; the speed is less than 14 km/h for 65% of the time.

(3) DEMOGRAPHICS

The area is covered by forest and grazing pastures that are used for the breeding of small mountain cattle. The population density is low, about 10 inhabitants/km². The nearest small village is located 600 m to the west.

(4) GEOLOGY AND TOPOGRAPHY

The 300 million year old granite faulted under Hercynian tectonic. A few centimetres of earth cover a few tens of centimetres thick altered granite (sand and argillous minerals).
HYDROGEOLOGY AND HYDROLOGY

There are no aquifers in this granitic region, except for local surface wet areas. There is a small creek, called Fouillouse, in the valley; it has an average flow of 300 m$^3$/h.

MISCELLANEOUS SITE PROBLEMS AND OBJECTIVES

(a) Types of facility: All types of mine/mill facility can be found on the site at Le Cellier. The area was in operation from 1956 to 1990. Heap leaching took place from 1970 to 1990. The mill was built in 1977 and was decommissioned in 1989–1990. The mill treated ore from three major open pit and/or underground mines located on the site or 10–80 km away. The types of facility and ore at the various sites are shown below.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Open pit mine</th>
<th>Underground mine</th>
<th>Mill leaching</th>
<th>Heap leaching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Le Cellier</td>
<td>X</td>
<td>X</td>
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<td>2285 t U (0.068%) tailings storage</td>
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<td>Le Villeret</td>
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<td>Linked with Le Cellier</td>
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<td>5 x 10$^6$ t total stripping; 422 t U (0.0306%)</td>
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<td>Pierres plantées</td>
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<td>1 x 10$^6$ t total stripping; 1280 t U (0.225%)</td>
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<td>Les Bondons</td>
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<td></td>
<td>3.7 x 10$^6$ t total stripping; 338 t U (0.0643%)</td>
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</tbody>
</table>

(b) Objectives: The following limits are prescribed by the regulators: (i) waste water quality: 30 mg/L suspended matter, pH: 6–8.5; (ii) local river water quality after discharge point: sulphate: <350 mg/L; Cl: <150 mg/L; dissolved U: 1.8 mg/L; dissolved $^{226}$Ra: 0.37 Bq/L; (iii) total added exposure to the public: 5 mSv/a. The following operational limits apply: (i) surface activity for materials to
be reused by the public: 2 Bq/cm² (alpha contamination); (ii) 700-900 counts/s SPP2 (scintillometer for gamma count), which for this site was estimated as being equivalent to 600 nGy/h. A further objective is to integrate the area into the landscape in order to minimize the visual impact.

(c) Cost of decommissioning: The total cost of decommissioning for the above listed sites (mill, open pit and underground mines, heap leaching piles) amounts to FF 200-350 × 10³/ha. Funds have been collected to cover 10 years of payment for treatment of water (acid, uranium and radium content of 200 000 m³/a); monitoring of the environment; and maintenance of the site.

Items (d) and (e) concern the Le Cellier site (66 ha), including the open pit and mill site as well as the heap leaching piles.

(d) Surface and groundwater controls: Water flowing on the surface of the mine site is potentially contaminated water from the surrounding area. Water from storage is isolated and treated before being discharged into the river. A compacted cover limits seepage through the residues.

(e) Monitoring and institutional control requirements: Depending on the water quality, the different water flows can be discharged directly, or be allowed to settle for sedimentation of the suspended matter and then controlled for chemical quality or treated for the pH and the radium and uranium content. One year after closeout, the water quality was good, even before treatment, but all the same funds are available for 10 years of water treatment. Monitoring of the site environment includes:

(i) Water quality controls on the river before and after the discharge point; groundwater controls on springs and in the piezometer drilled in the river water table and in a selected piezometer in the granitic basement;

(ii) Air quality measures using site dosimeters (alpha potential energy, external exposition and activity of long lived alpha emitters in dust). Measurements are sent to the regional authority (Direction régionale de l'industrie, de la recherche et de l'environnement (DRIRE)), which is in the process of examining the conditions for the licence.

(7) MINE

The following details concern the Le Cellier mining operations.

(a) Type/size: Underground mining started in 1956, followed by open pit extraction. The open pit was mined to a level of −105 m and underground mining to a level of −143 m.
(b) **Ore grade:** 3 321 000 t of ore containing 2285 t U (0.068%) (rich ore heap leaching followed by mill leaching and poor ore heap leaching).

(c) **Method of decommissioning:** From 1986 onwards, the open pit was used as the mill tailings pond. The sides of the open pit were first lined with mining debris to isolate the tailings from incoming water. Division of the pit into two parts allowed for alternate settling and covering with mining debris before further filling. At the end of these operations, the pond was used to gather contaminated (i.e. over public limits) materials and debris and non-reusable equipment from the mill. After grading the side walls, the whole pit was covered with compacted mining debris with a minimum slope of 1%. Revegetation was carried out by hydroseeding. The openings in the underground mining facilities were filled with mining debris; for the last few metres near the surface, backfilling was done with concrete.

(d) **Cost of decommissioning:** See (c) in item (6).

(e) **Surface and groundwater controls:** Surface water is prevented from seeping through the residues by compaction. Water overflowing out of the residues under the cover is collected separately for water treatment.

(f) **Monitoring and institutional control requirements:** See (e) in item (6).

(8) **MILL**

(a) **Type/size:** The mill is an acid leach plant with grinding to 500 μm (750 t/d).

(b) **Grade milled:** 0.15%.

(c) **Method of decommissioning:** The whole facility has been shut down. Some equipment has been reused in other uranium mining or milling facilities. About 355 t of iron equipment have been scrapped and 2000 t of metallic and concrete debris relocated with the residues in the Le Cellier open pit.

(d) **Cost of decommissioning:** See (c) in item (6).

(e) **Surface and groundwater controls:** See (d) in item (6).

(f) **Monitoring and institutional control requirements:** See (e) in item (6).
(9) TAILINGS IMPOUNDMENT(S) AND WASTE TREATMENT FACILITIES

(a) **Type of impoundment:** Until 1982, the mill tailings were dumped on the heap leach piles and managed with these materials (see item (11)). From 1983 onwards, the mill tailings were gathered in the open pit at Le Cellier (see item (7)).

(b) **Quantity and surface area:** The open pit contains $1.7 \times 10^6$ t of material, including mill tailings, some heap leach residues and sludge from the water treatment.

(c) **Activity and physical characteristics:** The mill tailings are less than 500 μm in size. The $^{226}\text{Ra}$ activity is 23.9 TBq (646.13 g of $^{226}\text{Ra}$).

(d) **Non-radiological contaminants:** Mainly ferrous sulphate.

(e) **Method of decommissioning:** See (c) in item (7).

(f) **Cover characteristics:** See (c) in item (7).

(g) **Cost of decommissioning:** See (c) in item (6).

(h) **Surface and groundwater controls:** See (e) in item (7).

(i) **Monitoring and institutional control requirements:** See (e) in item (6).

(10) MINING DEBRIS PILES

(a) **Type of pile:** Mine waste rock.

(b) **Quantity:** Only 120 000 t remain near Le Villeret.

(c) **Activity and physical characteristics:** The material is coarse (blasted from the open pit), with a grade of about 20 ppm of uranium (negligible activity).

(d) **Non-radiological contaminants:** None.

(e) **Method of decommissioning:** Waste rock debris has been used to cap all the decommissioned areas. The slopes of the remaining pile have been smoothed and revegetated to integrate the piles into the landscape.
(f) **Cover characteristics**: None.

(g) **Cost of decommissioning**: See (c) in item (6).

(h) **Surface and groundwater controls**: See (d) in item (6).

(i) **Monitoring and institutional control requirements**: See (e) in item (6).

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(11) **HEAP LEACH PILES**

(a) **Type of pile**: Depending on the location, the pile is built on compacted material lined with bitumen or on the natural surface (altered argillous granite) covered with a net of drain pipes.

(b) **Quantity, activity and surface area**: The area used for heap leaching covers 25 ha; $4 \times 10^6$ t of leached material contained 18 TBq of $^{226}$Ra (487 g of $^{226}$Ra). About $0.6 \times 10^6$ t of slurry from water treatment was relocated to the pile in 1982; it contains 1.2 TBq of $^{226}$Ra (32.5 g of $^{226}$Ra).

(c) **Physical characteristics**: The poor ore treated by heap leaching was not crushed.

(d) **Method of decommissioning**: In situ closeout. The cover provides hydraulic and mechanical protection.

(e) **Cover characteristics**: The total area was covered with a 0.4–0.6 m layer of compacted mining debris; a 0.3 m non-compacted layer, which allows the water to be drawn away from the surface; and a 0.1 m layer of earth for revegetation. The thicknesses were chosen according to the radiometric and permeability measurements taken on the test areas.

(f) **Cost of decommissioning**: See (c) in item (6).

(g) **Surface and groundwater controls**: Special attention was paid to the slopes (1% minimum is necessary to avoid the formation of ponds) and the surface pathways of rain water. Ditches were constructed to separate the water from outside the site, the surface water on-site and the water seeping through the piles; only the latter water is expected to be treated.

(h) **Monitoring and institutional control requirements**: See (e) in item (6).
(12) VICINITY PROPERTY REMEDIATION

No problems with the misuse of radioactive materials have arisen in the area. Mining debris (less than 100 ppm) can be removed from the site for public or private use, but such use is strictly limited to civil engineering operations; no construction is allowed.
GERMANY

The following is a report on the decommissioning and closeout of the Seelingstädt mill facility and the Königstein mine facility.

Seelingstädt mill facility

(1) LOCATION AND OWNERSHIP

The mill facility is located in the State of Thuringia in Germany at a latitude of 50°45’ North and a longitude of 12°12’ East; the altitude is 208–398 m above sea level. Prior to the reunification of Germany in 1990, the uranium mines and mills were 50% owned by the former USSR and 50% by the former German Democratic Republic. After reunification, ownership was transferred to the Ministry of Economics, Germany.

(2) CLIMATIC CONDITIONS

The mean annual precipitation is 658 mm, the mean temperature 7.6–8.0°C and the average wind speed 1.5–3.5 m/s.

(3) DEMOGRAPHICS

The surrounding area is densely populated. Several small villages with a total number of 2700 inhabitants are located less than 1 km from the mill site or the tailings management areas. The nearest City is Berga (5000 inhabitants), located 2.5 km from the main tailings impoundment. The City of Gera (135 000 inhabitants) lies 16 km to the north. Several main road and railway connections as well as electricity, drinking water and gas supply lines pass close to the site. The main land use of the surrounding area is agriculture.

(4) GEOLOGY AND TOPOGRAPHY

The site is located in the low metamorphic Saxo-Thuringian zone of the Central European Hercynian Belt. The geology of the Ronneburg ore body is determined by the Culmitch Fault (direction southeast to northwest), where Ordovician phyllites
lie next to Permotriassic sediments. The two tailings impoundments are located to the southwest of the fault in mined out open pits, where uranium mineralization has been found in a lens of Zechstein slates overlying the Ordovician phyllites. From these open pits a total of 12 000 t U has been mined. The mill site is situated to the northeast of the fault.

(5) HYDROGEOLOGY AND HYDROLOGY

The clay slate underlying the tailings impoundments and the mill site are considered to be rather impermeable. The main aquifer is of Culmitzsch sandstone to the southwest of the Culmitzsch Fault. It is used for the non-drinking water supplies of the adjacent villages. Deep wells are found to the south of Gera. Water is being discharged into several small creeks. The main stream receiving water discharges from the Seelingstädt mill (as well as discharges from the mining site Ronneburg, 10 km to the north of Seelingstädt) is the Weiße Elster. Its average flow rate is 30 000 m$^3$/h. At present, there is no direct use of this water as drinking water. The Weiße Elster eventually flows into one of the major German rivers, the Elbe (some 200 km to the north of the mining area).

(6) MISCELLANEOUS SITE PROBLEMS AND OBJECTIVES

Not applicable.

(7) MINE

Not applicable.

(8) MILL

(a) Type/size: Two types of ore have been processed in the Seelingstädt mill: carbonate ores with an average of 16.5% dolomite and 3.8% pyrite, and silicate ores with 3.5% dolomite and 4.7% pyrite. A total of $52 \times 10^6$ t of carbonate ores with an average grade of 0.069% has been processed by alkaline leaching (soda consumption, 23 kg/t) using a combination of atmospheric and pressure leaching. Fifty seven million tonnes of silicate ores with an average grade of 0.1034% have been leached under atmospheric pressure with sulphuric acid (consumption greater than 100 kg/t) using NaClO$_3$ as the oxidizing agent. Uranium was extracted by ion exchange (RIP process) and precipitated with ammonia. The total uranium production of the mill was 85 000 t.
(b) Grade milled: See (a) in item (8).

(c) Method of decommissioning: The mill started operation in 1960. Uranium production was shut down at the end of 1991. The currently preferred aim of future remedial work is the complete cleanup of the site, including the demolition of all contaminated buildings and the excavation of contaminated soils. Estimates for costs, surface and groundwater controls as well as monitoring and institutional control requirements cannot as yet be given.

(9) TAILINGS IMPOUNDMENT(S) AND WASTE TREATMENT FACILITIES

(a) Type of impoundment: The mill in Seelingstädt discharged its tailings into two open pits from uranium mining. Each is divided into two impoundments by a separating dam. To increase the volume in the impoundments, perimeter dams were built, mainly from waste rock. The smaller impoundments, Trünzig A and B, were used from 1960 to 1967. Thereafter, the larger Culmitzsch A and B impoundments were used.

(b) Quantity and surface area: See (c) in item (9).

(c) Activity and physical characteristics: The average $^{226}$Ra activity in the tailings is about 10 Bq/g. The residual uranium activity is about 1 Bq/g (the extraction efficiency of the mill was about 90%). Information is provided below.

<table>
<thead>
<tr>
<th>Pond</th>
<th>Mass of tailings $(10^6 t)$</th>
<th>Volume $(10^6 m^3)$</th>
<th>Surface area (ha)</th>
<th>Surface and drainable pore water $(10^6 m^3)$</th>
<th>Total activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Culmitzsch A</td>
<td>63</td>
<td>61</td>
<td>158</td>
<td>20</td>
<td>6840 t U;</td>
</tr>
<tr>
<td>Culmitzsch B</td>
<td>27</td>
<td>24</td>
<td>90</td>
<td>8</td>
<td>981 TBq of Ra</td>
</tr>
<tr>
<td>Trünzig A</td>
<td>13</td>
<td>13</td>
<td>65</td>
<td>2</td>
<td>2205 t U;</td>
</tr>
<tr>
<td>Trünzig B</td>
<td>6</td>
<td>6</td>
<td>51</td>
<td>2</td>
<td>175 TBq of Ra</td>
</tr>
<tr>
<td>Total</td>
<td>109</td>
<td>104</td>
<td>364</td>
<td>32</td>
<td></td>
</tr>
</tbody>
</table>

(d) Non-radiological contaminants: The main non-radiological contaminants are sulphates and chlorides. The sulphate concentration in the water of the Culmitzsch
A and B tailings ponds is between 7 and 9 g/L and the chloride concentration is about 1.4 g/L. The arsenic content of the water is 0.1 mg/L in Culmitzsch A and 1.3 mg/L in Culmitzsch B.

(e) **Method of decommissioning:** As an immediate measure for the prevention of dust erosion, the beaches of the tailings impoundments were covered with a thin layer of topsoil. Currently, viable options for the reclamation of the tailings areas are being identified and evaluated. The main technical problems that are being addressed in the current research work are the stability of dams, the hydrogeological situation and the methods for dewatering of the tailings. If technically feasible, the preferred option would be the in situ reclamation of the tailings ponds by dewatering and covering.

(10) **MINING DEBRIS PILES**

(a) **Type of pile:** Mine waste rock.

(b) **Quantity and surface area:** In the vicinity of the tailings impoundments there are several waste rock piles that originate from the mining of the open pits. The total surface area is 440 ha and the total volume \(67 \times 10^6\) m\(^3\) (without Sorge-Settendorf).

(c) **Activity and physical characteristics:** The average activity is below 1 Bq/g of \(^{226}\)Ra.

(d) **Method of decommissioning:** The waste rock piles are integrated into the perimeter dams of the tailings impoundments. The reclamation concept for these piles will depend on the reclamation of the tailings areas. One possible option is the use of at least part of the waste rock for covering of the tailings impoundments.

(11) **MONITORING**

There is an environmental monitoring network of sampling instruments in the vicinity of the mill site, tailings and waste rock areas. In total, there are 68 radon measurement devices; 17 measurement devices for radium in dust sedimentation; 13 measurement devices for long lived alpha emitters in airborne dust; 27 surface water sampling devices; and 307 groundwater sampling devices. The sampling network was established according to the necessities of environmental monitoring during the operation and closeout phases. After the remedial work is completed, an assessment of the long term requirements for environmental monitoring will be made. The final monitoring concept for the post-reclamation phase will then be defined and incorporated into a long term institutional control programme.
Königstein mine facility

(1) LOCATION AND OWNERSHIP

The mine is located in the State of Saxonia in Germany at a latitude of 51° North and a longitude of 14° East. The mine is owned by the Ministry of Economics, Germany.

(2) CLIMATIC CONDITIONS

The mean annual precipitation is 659 mm and the mean temperature 8°C.

(3) DEMOGRAPHICS

Within a distance of 10 km from the mine site there are several villages with a total of 25 000 inhabitants. About 10 km to the west lies the City of Pirna with a population of 50 000.

(4) GEOLOGY AND TOPOGRAPHY

The mine is situated in a basin that is part of the Elbtal-Graben system, a north-west to southeast trending structure in Palaeozoic basement rock. The basin is filled with sediments of upper Cretaceous age. These sediments consist of four series of quartz sandstones with small intercalations of clay, siltstone and limestone.

(5) HYDROGEOLOGY AND HYDROLOGY

In the area around Königstein there are four aquifers. All (the fourth only at some distance) are used for the drinking water supply. The size of the upper two aquifers is small. The main drinking water source is the third aquifer. To date, this aquifer has not been influenced by mining with respect to water quality, but the level has been lowered by mine dewatering (20–60 m in a depression, with a length of 2.5 km in a north–south direction and a length of 8.5 km in an east–west direction).

The ore body is located within the fourth aquifer, which has been strongly influenced by mining (a depression of 60–120 m, with a length of 11 km in a north–south direction and 17 km in an east–west direction; in the vicinity of the ore body it is completely dewatered).
Both the third and fourth aquifer are in contact with the nearby River Elbe (with an average flow rate of 319 m$^3$/s). Mine water discharges are directed into the Elbe after treatment.

(6) MISCELLANEOUS SITE PROBLEMS AND OBJECTIVES

Not applicable.

(7) MINE

(a) Type/size: Conventional underground mining in Königstein started in 1964. From the beginning of the 1970s, experiments with in situ leaching were conducted. Since 1984, uranium has been produced only by in situ leaching. The mined part of the ore body has a surface area of 5 km$^2$ and its height varies between 0 and 20 m. Mine workings have been developed at depths of 150-300 m. The average ore grade is 530 ppm. The mine in Königstein produced a total of 18 100 t U (70% by conventional mining and 30% by in situ leaching) (31 December 1991).

(b) Ore grade: See (a) in item (7).

(c) Method of decommissioning: Since in situ leaching operations cannot be shut down abruptly, reclamation work is being performed stepwise. The main objective of the decommissioning work will be to protect the third aquifer (major drinking water supply) from unacceptable contamination. The necessary reclamation measures have first to focus on approximately $1.9 \times 10^6$ m$^3$ of acidic solution that is still contained in the leaching circuits and in the pore spaces within the ore body. In addition, consideration will have to be given to what extent mine openings crossing the aquiclude between the third and fourth aquifer, as well as other damage caused to the aquiclude by mining, can and have to be sealed in order to provide long term isolation of the third from the fourth aquifer.

(8) MILL

Not applicable.

(9) TAILINGS IMPOUNDMENT(S) AND WASTE TREATMENT FACILITIES

Not applicable.
(10) MINING DEBRIS PILE

(a) Type of pile: Mine waste rock.

(b) Quantity and surface area: The waste rock pile occupies a surface area of 24.2 ha in a valley. The total amount of material deposited on the pile is $3.6 \times 10^6$ m$^3$. This material consists of $1.4 \times 10^6$ m$^3$ of waste rock (50 ppm of uranium and 0.5 Bq/g of radium), $1.9 \times 10^6$ m$^3$ of residues from heap leaching (105 ppm of uranium and 3.2 Bq/g of radium) and $0.3 \times 10^6$ m$^3$ of sludges from the water treatment facility (160 ppm of uranium and 5 Bq/g of radium).

(c) Activity: See (b) in item (10).

(11) HEAP LEACH PILES

(a) Type of pile: In Königstein, there are two heap leach areas (1 ha each) with a prepared base. At these locations, heap leaching with sulphuric acid is being performed. The ores that are being leached here originate from the mining necessary to prepare new leaching blocks for the in situ leaching process. The residues are being deposited on the waste rock pile (see (b) in item (10)).

(b) Quantity and surface area: See (b) in item (10).

(c) Method of decommissioning: Decommissioning will include the cleanup of the heap leach area (excavation of the contaminated base). Residues deposited at the waste rock pile will be reclaimed, together with the waste rock pile itself.

(12) MONITORING

An environmental monitoring network of sampling instruments in the vicinity of the mine site, heap leach and waste rock area is currently under construction. In total, there will be 46 radon measurement devices; nine measurement devices for mine ventilation exhausts; seven surface water sampling devices; and 102 groundwater sampling devices.

This sampling network is being established according to the necessities of environmental monitoring during the operation and closeout phases. After the remedial work is completed, an assessment of the long term requirements for environmental monitoring will be made. The final monitoring concept for the post-reclamation phase will then be defined and incorporated into a long term institutional control programme.
SLOVENIA

The following is a report on the decommissioning/closeout of the Žirovski vrh mine/mill in Slovenia.

(1) LOCATION AND OWNERSHIP

The Žirovski vrh uranium mine is located in the valley of the Brebovščica Creek between Gorenja vas and Lučine, 20 km to the southwest of Škofja Loka, Slovenia. Preliminary geological exploration in the Žirovski vrh deposit area started around 1960 and was intensified in 1979. The ore was mined from 1982 to 1990. Milling operations began in late 1984 and continued until shutdown in June 1990. The mine/mill facility is located at a latitude of 46°05' North and a longitude of 14°10' East. Its full name is Rudnik urana Žirovski vrh (Ružv) and it is owned by the Ministry of Environment and Regional Planning, Slovenia.

(2) CLIMATIC CONDITIONS

Slovenia has a mixed continental-Mediterranean climate, hot and wet during the summer and cold with snow during winter. The relative humidity is 80%.

(a) Precipitation: The annual precipitation is 1900 mm, with a range of 1390-2460 mm. The maximum 24 hour rainfall is 280 mm and the maximum depth of snow 1400 mm. The mean annual evaporation is 546 mm.

(b) Temperature: The mean annual temperature is 8.6°C. The mean temperatures are -0.7°C in January and 18.5°C in July. The maximum estimated high and low temperatures are 37 and -30°C, respectively.

(c) Wind: The wind speed is predominantly low, 70% south-north, 30% windless.

(3) DEMOGRAPHICS

Ore and uranium production are situated in a densely populated farming area. Adjacent to the site (0.5 km radius) live 200 people. A small community of 300 people live 1 km away from the site and Gorenja vas, with 1000 inhabitants, is 2 km away.
(4) GEOLOGY AND TOPOGRAPHY

The mine is located on the northeastern slopes of the Žirovski vrh Mountain at an altitude of 430–600 m. Because of the humid, subalpine climate, weathered rocks of a thickness of a few metres are found. Some farms, surrounded with meadows and fields, are scattered on the slopes of the mountain; most of the area is covered by woods. The massif of Žirovski vrh belongs to the Žirovsko-Trnovska nappe overthrust on Upper Triassic rocks. In the deposit, there are mainly conglomerates, sandstones and mudstones of Middle Permian age (Groeden). The partially folded structure is cut by smaller faults with shifts of several tens of metres.

(5) HYDROGEOLOGY AND HYDROLOGY

Clastic sediments are tight and permeability is very low. The main inflow of mine water that appears in the shafts is from the surface, from boreholes and from fissures along the faulted zones. Mine water runoff varies from 15 to 25 L/s. Surface runoff and mine water drain to the Brebovščica Creek, which discharges 2 km north to the River Sora. The watersheds of Brebovščica measure 14.5 km². An annual runoff of 45 L·s⁻¹·km⁻² has been determined.

(6) MISCELLANEOUS SITE PROBLEMS AND OBJECTIVES

The authorized limits for air protection (radon exhalation rate) and surface and groundwater protection have not as yet been issued by the authorized authorities.

(7) MINE

(a) Type/size: All the uranium ore was removed underground from an ore bearing body approximately 2000 m long, 180 m deep and 100 m wide. Production varied over the years, depending on the mining methods used. The total production between 1960 and 1980 was 16 500 t of ore, and between 1981 and 1991, 613 000 t of ore. The main underground operations were accessed by tunnel P-11; auxiliary structures include four vertical shafts for fresh air inlet, a tunnel for mine water flow, two tunnels for ventilation and another for manned access.

(b) Ore grade: The average ore grade was 0.087%; the overall average per site ranged from 0.05 to 0.2%.
(c) **Method of decommissioning:** All the opened stopes, where the ore has been exploited, will be backfilled with mine waste rock (ca. 200 000 m$^3$). The horizontal openings will be backfilled with 20 m of waste rock and the vertical openings sealed with waste rock and reinforced concrete plates. The other underground complex might be used for the disposal of various waste materials. Before the final closing of the mine, the boreholes will be used for proper dewatering.

(d) **Surface and groundwater controls:** All the mine water will run off through one tunnel and will be sampled for uranium and radium for a long period.

(e) **Monitoring and institutional control requirements:** During mine closeout, monitoring is similar to that of production monitoring. Active mine works are controlled every day, i.e. the safety conditions, mine ventilation and carbon monoxide concentration. Water is collected at the lowest point in the mine and is treated mechanically from suspended solids. Runoff mine water is controlled for uranium, radium and sulphate/chloride/ferric/ammonia ions on a monthly basis.

8) **MILL**

(a) **Type/size:** Ore processing started in late 1984 and continued until June 1990. The process flowsheet includes crushing and grinding, acid leaching, vacuum belt filtration for solid/liquid separation, solvent extraction and ammonia precipitation. The raffinate was neutralized and completely recycled. Tailings with a 20% moisture content were transported by truck to the disposal site.

(b) **Grade milled:** The overall mill grade averaged 0.09% U$_3$O$_8$. A total of 610 000 t of ore was milled, producing 450 t of yellow cake. The mill capacity was 630 t/d.

(c) **Method of decommissioning:** The mill liquids were neutralized and decontaminated. Useful mill materials will be decontaminated; the same is planned for the mill area and buildings. Waste materials will be disposed of in the mine.

(d) **Surface and groundwater controls:** The mill is located on a valley plateau between two water streams. These are sampled for chemical pollutants on a monthly basis. Uranium and radium are sampled daily for composite and monthly analyses. No regular control will be provided after decommissioning of the mill.

(e) **Monitoring and institutional control requirements:** Decommissioning of the mill is in progress. Equipment for reuse is decontaminated to less than 4 Bq/dm$^2$ of alpha activity. Scrap for recycling in a steel smelting plant must be below 40 Bq/dm$^2$ of alpha activity. In the building, the gamma radiation level should be
below 0.3 μSv/h and the radon concentration below 250 Bq/m³. No monitoring will
be done after decommissioning.

(9) TAILINGS IMPOUNDMENT(S) AND WASTE TREATMENT
FACILITIES

(a) Type of impoundment: The tailings impoundment is situated 3 km from the
mill on a hill slope 530 m above sea level. During construction, drainage pipes for
groundwater protection were installed and impermeable material graded. Drainage
strips of synthetic ribbed insert and other materials were placed on impermeable
indigenous material to avert the porous moisture water from the tailings. Levelling
of the material was performed by bulldozer. The slopes were covered with soil and
grass was seeded to protect the surface against rainfall runoff. The surface waters
were averted via a drainage collection system to the control pond. Clear water over-
flowed to the Todrašica stream or was reused in the mill.

(b) Quantity and surface area: During the short operational life of the tailings
impoundment, about 700 000 t of mill tailings and road material were placed. The
tailings surface is flat, with a slight slope for rainfall dewatering. The area of the
site is 3.5 ha.

(c) Activity and physical characteristics: Practically all the tailings material is
sand and slimes under 28 mesh. Radon emanation is 1–10 Bq·cm⁻²·s⁻¹ from the
open tailings areas; the average activity for ²²⁶Ra is 8700 Bq/kg.

(d) Non-radiological contaminants: The major ions are sulphates, calcium, mag-
nesium and ammonium. Other heavy metal contaminants are of low concentration.

(e) Method of decommissioning: A project for the permanent rehabilitation of the
mill tailings impoundment is under preparation. On completion, the project should:

(i) Provide geomechanical stability to the area from sliding by using ground-
water drainage tunnels and drainage drillings
(ii) Protect the mill tailings impoundment against background waters
(iii) Prevent the leaching of soluble toxic compounds into underground and
surface waters
(iv) Cover the tailings impoundment with natural materials to prevent exces-
sive exhalation of radon
(v) Recultivate the surface to prevent erosion caused by rainfall.

(f) Cover characteristics: The multilayer cover will be composed of the follow-
ing natural materials: compacted clay: 0.3 m; small rocks for water drainage:
0.25 m; rocks and sand for biological protection: 0.25 m; soil and rock materials: 1 m; and humus: 0.25 m. The surface will be grass seeded.

(g) **Surface and groundwater controls:** The mill tailings will be isolated from surface and rain waters to prevent the dissolution of contaminants. Underground water will be controlled and maintained at a low level by underground tunnels and drainage drill holes.

(h) **Monitoring and institutional control requirements:** Sampling of underground and surface drainage waters will continue on a monthly basis until the remedial work is completed. Concentrations of uranium, radium, NH₄ and SO₄ as well as the pH have been determined. The exact plan for future monitoring has not as yet been determined. Mechanical, chemical and radiological monitoring is foreseen on a yearly basis.

(10) MINING DEBRIS PILES

(a) **Type of pile:** Mine waste rock and plant process water neutralization waste (gypsum, ferric oxides, etc.).

(b) **Quantity and surface area:** Three storage areas were developed for mining debris during the operational life of the mine. Two (3.4 ha, 300 000 t of mining debris) are temporary and the third (3.7 ha, 1.5 x 10⁶ t of mining debris) is permanent.

(c) **Activity:** The uranium content is 0.006%.

(d) **Method of decommissioning:** The waste is primarily silicon oxides with small amounts of iron, carbonates and sulphides. Generation of acid is not expected. Solid sulphates and other ions such as calcium, magnesium and iron are present from neutralized raffinate in the mill.

(e) **Cover characteristics:** A combination of clay and rock materials will be placed over the mine debris pile.

(f) **Surface and groundwater controls:** Not known in detail.

(g) **Monitoring and institutional control requirements:** The mining debris and mine waste pile will be isolated from surface and rain waters by a multilayer cover to prevent the dissolution of contaminants. The mining debris pile area is dewatered into a small stream running into the Brebovščica Creek. After the remediation work
is completed, chemical and radiological monitoring of the water will continue on an annual basis. The same is foreseen for radon monitoring of the covered pile.

(11) VICINITY PROPERTY REMEDIATION

(a) Type of remediation: It is expected that all the buildings will be used for industrial purposes after the remedial work is completed. There is no need for any remedial action to be taken outside the property limits.

(b) Monitoring and institutional control requirements: A plan will be drawn up to control the future health of mine workers. Other than stated previously, there are no future requirements for ongoing monitoring of the vicinity property.
SPAIN

There is only one uranium mill facility undergoing decommissioning in Spain. This facility is known as the Andújar uranium milling plant. During operation, it was not associated with a specific mine, but was supplied with ore by different nearby mining sites. These mines have been abandoned and will be decommissioned in the future. The following report provides data on the closeout of the Andújar mill facility and the associated tailings pile. No data are presented for the mining sites, since remedial investigations are only starting.

(1) LOCATION AND OWNERSHIP

The Andújar plant is in the province of Jaén (Andalucia) on the southern floodplain of the River Guadalquivir, 1.5 km to the south of the urban centre of the town of Andújar. The plant is located at a latitude of 38°1’12” North and a longitude of 4°3’18” West.

The site is trapezoidal in shape, covers a flat area of approximately 17.5 ha and contains a disused processing plant, the tailings pile and associated housing and administrative buildings.

The owner of the facility was the Junta de Energía Nuclear and the site is now being remediated by the Empresa Nacional de Residuos Radiactivos S.A. (ENRESA).

(2) CLIMATIC CONDITIONS

The climate of the Andújar area is characterized by low to medium precipitation, abundant sunshine, medium relative humidity and moderate to high temperatures, with large diurnal and annual ranges. The regional climate may be classified as Mediterranean subtropical, with a dry and warm summer.

The Andújar area exhibits a large diurnal range in temperatures, with a mean daily minimum of 25°C and a mean daily maximum of 12°C. The mean daily average is 17.6°C, with a maximum of 42°C and a minimum of 0°C.

Most of the precipitation in the Andújar area occurs during the autumn and winter seasons. The annual average precipitation is 550 mm, with a maximum monthly precipitation of 93.4 mm in December. The mean annual potential evapotranspiration in the area reaches 823 mm, of which about 50% occurs between May and September.
(3) DEMOGRAPHICS

The Andújar plant is located approximately 1.5 km to the south of the centre of the town of Andújar, which has a population of 32,000. There are four additional communities within an 8 km radius of the plant: Arjonilla is the most populated, with 4,000 inhabitants. The site is surrounded by olive fields and an olive oil processing factory is located nearby.

(4) GEOLOGY AND TOPOGRAPHY

The Andújar site lies on Quaternary alluvial clays and gravel terraces underlain by Miocene clays and marls. The thickness of the alluvial clays ranges from 1.8 to 4.0 m and that of the gravels from 2.0 to 4.0 m. The Miocene strata consist of approximately 200 m of ‘blue’ marls that are moderately jointed and are considered to have a very low permeability on a regional scale.

(5) HYDROGEOLOGY AND HYDROLOGY

The site is located on the floodplain of the River Guadalquivir and is about 150 m from the migration course of a large meander. The maximum annual flows in the river are of the order of 500–600 m$^3$/s, and the estimated flow for a 500 year return period is 5400 m$^3$/s. The shallowest aquifer beneath the site lies in the gravel terrace formation and its flow is directed towards the river.

(6) MISCELLANEOUS SITE PROBLEMS AND OBJECTIVES

The average flux of radon over the tailings ranges between 6 and 10 Bq·m$^{-2}·$s$^{-1}$ (approximately 150 and 250 pCi·m$^{-2}·$s$^{-1}$). The average concentration of radon in air inside the site is about 335 Bq/m$^3$.

The results of the radiological monitoring programme indicate that in the urban centre of Andújar the average level of gamma radiation is 1.2 mSv/a and the maximum concentration of radon daughters is about 6 mWL.

Analyses of groundwater samples from 14 wells (three of which are near the facility) show that the concentration of radium is, in all cases, lower than 0.1 Bq/L (2.7 pCi/L). The maximum average yearly concentration of uranium found in two wells next to the facility is about 7 Bq/L (189 pCi/L). None of the wells is used for the regular supply of water.
The main objectives/criteria established by the regulatory authorities were as follows:

(a) **Dispersion control:** to prevent inadvertent human intrusion and dispersion of contaminated materials by wind and water erosion
(b) **Long term radiation protection:** to achieve an effective equivalent dose to the individual in the critical group below 0.1 mSv/a
(c) **Design life:** to remain stable for 1000 years to the extent reasonably achievable and in any case for at least 200 years
(d) **Soil cleanup:** to reduce the residual concentration of $^{226}\text{Ra}$ in land, averaged over an area of 100 m$^2$, so that the background level is not exceeded by more than 0.18 Bq/g (5 pCi/g) (averaged over the first 15 cm of soil) and is less than 0.55 Bq/g (15 pCi/g) (averaged over 15 cm thick layers of soil more than 15 cm below the surface)
(e) **Radon control:** to reduce radon flux over the surface of the final pile to an average release rate of less than 0.74 Bq·m$^{-2}$·s$^{-1}$ (20 pCi·m$^{-2}$·s$^{-1}$)
(f) **Groundwater quality protection:** to control groundwater contamination so that background water quality or maximum concentration levels are achieved in the long term; these levels are: combined $^{226}\text{Ra}$ and $^{228}\text{Ra}$: 0.18 Bq/L (4.86 pCi/L); combined $^{234}\text{U}$ and $^{238}\text{U}$: 1.2 Bq/L (32.4 pCi/L); and the gross alpha activity, excluding radon and uranium: 0.5 Bq/L (13.5 pCi/L)
(g) **Long term maintenance:** to minimize the need for long term maintenance
(h) **Construction work:** to minimize hazards to the workers and the environment
(i) **Regulations:** to comply with other applicable and relevant Spanish regulations governing air and water quality in non-radiological aspects.

Groundwater quality protection, for short term conditions, requires that the remedial work be designed to limit infiltration to ensure that, at the end of the compliance period, the combined $^{234}\text{U}$ and $^{238}\text{U}$ concentration in the groundwater complies with the following conditions:

(i) Less than 6.15 Bq/L (166 pCi/L) at the point of compliance, located at the down gradient boundary of the disposal site
(ii) Less than 3.5 Bq/L (94.5 pCi/L) at the wells located in the vicinity of the site.

Monitoring during the compliance period (minimum 10 years), to confirm the adequacy of the closure work and to verify design performance, is also required.

(7) MINE

Not applicable.
(8) **MILL**

(a) **Type/size:** The Andújar plant was designed for processing low grade uranium ore (0.15% \( \text{U}_3\text{O}_8 \)) and produced 80% concentrate of \( \text{U}_3\text{O}_8 \) in the form of sodium and ammonium uranate at a rate of 60–80 t/a. The plant became operational in 1959 and continued in operation until 1981. Recovery of the uranium involved sulphuric acid leaching, followed by ion exchange or tertiary amine/kerosene extraction. Solid wastes were stored in the tailings piles and liquid wastes were treated before disposal into the River Guadalquivir.

(b) **Grade milled:** The overall mill grade averaged 0.123%. A total of \( 1.2 \times 10^6 \) t of uranium ore was processed to produce 1350 t of \( \text{U}_3\text{O}_8 \) with a fineness of 80–85%.

(c) **Method of decommissioning:** The mill equipment, buildings and process facilities have been dismantled and demolished and will be placed in a pile adjoining the main tailings pile. The major activities involved were decontamination/cleanup, dismounting and cutting of the equipment, demolition of structures, transportation of debris to the tailings pile and confinement in a cement matrix. Dismantling and demolition of mill buildings has been completed. Metal wastes are cemented at the final disposal location and demolition debris is stockpiled, pending final placement in the tailings pile.

(d) **Cost of decommissioning:** The overall decommissioning cost for the Andújar mill was Ptas 330 \( \times 10^6 \).

(e) **Surface and groundwater controls:** See item (6).

(f) **Monitoring and institutional control requirements:** An extensive environmental monitoring network for air, surface and groundwater control has been established according to the requirements of the closeout phase. After the remedial work is completed, the long term requirements for environmental monitoring and institutional control will be defined.

(9) **TAILINGS IMPOUNDMENT(S) AND WASTE TREATMENT FACILITIES**

(a) **Type of impoundment:** All the solid wastes generated during the plant’s operation (\( 1.2 \times 10^6 \) t) were deposited (by hydraulic filling) in the tailings pile, which covers an area of 9.4 ha and has a total volume of 980 000 m³. The pile was constructed in five cells (by the upstream method) to a height of 20 m in the central and
eastern parts and to a height of 10 m in the western part. Each individual cell is confined by a peripheral dyke and the tailings slurry was deposited using multiple discharge perimeter spigotting. The side slopes vary from 25 to 35° and are currently covered with asphalt.

(b) **Quantity and surface area:** See (a) in item (9).

(c) **Activity and physical characteristics:** The total activity contained in the tailings is estimated at $2 \times 10^{14}$ Bq (5400 Ci) and radium measurements indicate an average radium concentration of 13 Bq/g (345 pCi/g) in the pile. Tailings consist of sands, silty sands, clayey silts and silty clays. Particle size measurements in the tailings indicate a distribution of 41% sand and 59% silts/clays at the edges of the pile, and 22% sand and 78% silts/clays at the central portions of the pile.

(d) **Method of decommissioning:** The remedial action plan proposed for the Andújar mill site will consist of stabilizing and consolidating the uranium mill tailings and contaminated materials in place. The actual tailings pile will be reshaped by flattening the side slopes to improve stability. Mill equipment, buildings and process facilities will be dismantled and demolished, and then placed in a pile adjacent to the main tailings pile. Off-pile contaminated soils will be excavated and placed on top of the tailings pile to reduce the radon flux. The final pile configuration has been designed to minimize the movement of tailings and the size of the restricted disposal area. The pile will be constructed with 4% top slopes and 20% side slopes, providing sufficient static and dynamic slope stability without requiring excessively large rocks to resist erosion. The pile will be covered with a multilayer system to meet the three simultaneous demands of erosion control, infiltration and radon control. The top slope cover consists of, from top down, a 50 mm erosion barrier of mixed gravel and soil; a 500 mm vegetation growth and desiccation protection zone of random soil; a 250 mm filter of clean sand; a 300 mm biointrusion barrier of coarse rock; a 250 mm drain of clean sand; and a 600 mm radon and infiltration barrier of silty clay. The most significant benefits of this cover are its ability to deal effectively with vegetation and to reduce infiltration to the cell because of effective evapotranspiration. From top down, the side slope cover consists of 30 mm of soil to migrate into the rock and help support vegetation; a 300 mm erosion barrier of coarse rock; a 500 mm vegetation growth and desiccation protection zone of random soil; a 250 mm filter of clean sand; a 300 mm biointrusion barrier of large rocks; a 250 mm drain of clean sand; and a 600 mm radon and infiltration barrier of silty clay. The advantages of this cover include protection of the radon infiltration barrier from desiccation and the existence of a controlled zone (the random soil) for vegetation that might establish through the riprap and help reduce the visual impact of the remediated pile. Decommissioning started in February 1992 and is expected to be finished in early 1994.
(e) **Cover characteristics:** See (d) of item (9).

(f) **Cost of decommissioning:** The overall cost for closeout of the tailings pile is estimated to be about Ptas $1700 \times 10^6$.

(g) **Surface and groundwater controls:** Protection against upland watershed runoff is provided by channelling runoff around and away from the pile via drainage diversion wales along the perimeter of the pile. Protection against floods associated with the River Guadalquivir is provided by a rock apron around the perimeter of the pile and riprap layers on the sideslopes.

(h) **Monitoring and institutional control requirements:** See (f) in item (8).
UNITED STATES OF AMERICA

This report describes the decommissioning/closeout of the Green River, Utah, UMTRA site in the USA. UMTRA is a project of the DOE (Figs A-4 and A-5).

(1) LOCATION AND OWNERSHIP

The Green River mill and disposal cell sites are located approximately 1.6 km (1 mile) to the southeast of the City of Green River, Utah, in Grand County, at a latitude of 38°59'59'' North and a longitude of 110°08'20'' West. The owner of the facility was the Union Carbide Corporation. The site was remediated by the DOE.

(2) CLIMATIC CONDITIONS

The climate is arid with large ranges in daily and annual temperatures.

(a) Precipitation: The average annual precipitation is 15.24 cm (6 inches) and the average snowfall 25.4 cm (10 inches). The average annual evaporation total is approximately 152.4 cm (60 inches). Rainfall is fairly evenly distributed throughout the year, with slightly higher amounts of precipitation in August and September. Summer rains typically occur as thunderstorms that are limited in extent, but which can produce flash floods. The maximum snowfall occurs in January.

(b) Temperature: Annual temperatures average 11°C (52°F), with a range of -5°C (23°F) in January to 25°C (78°F) in July. June, July and August are the warmest months, averaging 32–35°C (90–96°F). The coldest months are generally December and January, with average maximum temperatures of 5 and 3°C (41 and 37°F), respectively. Temperature extremes can be as low as -32°C (-25°F) and as high as 42°C (107°F).

(c) Wind: The wind conditions are generally calm, up to 4.8 km/h (3 miles/h) over half of the time, with infrequent strong winds. The strongest winds are likely to occur between March and June. No single wind direction predominates, although winds are most frequently from the southwest, south and west.

(3) DEMOGRAPHICS

The disposal site and former mill location are approximately 1.6 km (1 mile) to the southeast of Green River. Land uses in and immediately adjacent to the city
FIG. A-4. Location of the Green River, Utah, tailings site.
FIG. A-5. Details of the Green River, Utah, disposal site area.
are primarily residential, agricultural and commercial. Approximately 80% of the land in the area is owned by the Federal Government, 13% by the State of Utah, and 7% is privately owned. The primary land use is irrigated cropland: 876 ha (2165 acres); pastureland: 184 ha (455 acres); and urban areas: 160 ha (395 acres).

Historically, population growth in the area has been related to uranium mining and milling activities. Population levels began to decline in the 1980s as a result of the decrease in energy exploration and development, closure of area mines and lack of other employment opportunities. In 1986, the population of Green River was 850 residents.

(4) GEOLOGY AND TOPOGRAPHY

The mill and disposal sites are located in the Gunnison Valley, approximately 0.8 km (0.5 mile) east of the Green River, at an elevation of 1244 m (4080 ft) above mean sea level. The valley is bordered to the north by the Book Cliffs, which are 1951 m (6400 ft) high, and to the south by the cliffs and mesas of the Green River. Vegetation is sparse, with few trees other than those growing along the river.

The sites are located in the northern part of the Canyon Lands section of the Colorado Plateau physiographical province. The Colorado Plateau is a major tectonic block comprised of Palaeozoic and Mesozoic sedimentary rocks underlain by a core of Precambrian rocks that lies across the States of Utah, Arizona, New Mexico and Colorado.

The sites are located on a slope between an upper abandoned river terrace and the present floodplain of the Green River and its local tributary, Brown's Wash. The sites lie on Quaternary upper terrace deposits and floodplain alluvium and on Cretaceous Mancos shale and Dakota sandstone bedrock.

(5) HYDROGEOLOGY AND HYDROLOGY

Within the upper 61 m (200 ft) of the underlying Cretaceous and Quaternary sediments, there are four distinct water bearing units. The upper shallow unconfined groundwater is present in Brown's Wash alluvium, and is limited by the lateral extent of the alluvium. Confined and semi-confined groundwaters are present in the three underlying hydrostratigraphical units. Tailings seepage has contaminated groundwater in the upper two units; however, the background water quality is also poor, indicating another nearby source of contamination and naturally occurring contaminants. These aquifers are not used because the groundwater quality is poor; most drinking water is supplied by the city from upstream river sources. There is no current use of any waters from Brown's Wash.
The surface water features in the area include the Green River, Brown’s Wash and several ephemeral drainages. In the vicinity of the sites the Green River has a drainage area of 105 128 km² (40 590 mile²), while Brown’s Wash, an intermittent tributary of the Green River, has a drainage area of 220 km² (85 mile²). The Green River’s recorded average maximum monthly and average mean monthly flows, taken from a United States Geological Survey (USGS) gauging station 975 m (3200 ft) upstream from the confluence with Brown’s Wash, were 693 and 526 m³/s (24 480 and 18 580 ft³/s), respectively. On 27 June 1917, a peak flow of 1928 m³/s (68 100 ft³/s) was recorded. The disposal cell is located 30.48 m (100 ft) above and 91.44 m (300 ft) away from the channel of the Green River, negating concern for flood impacts. Data taken from a former USGS gauging station operated on Brown’s Wash recorded average maximum monthly and average mean flows of 1.95 and 0.01 m³/s (69 and 3.6 ft³/s), respectively.

(6) MISCELLANEOUS SITE PROBLEMS AND OBJECTIVES

The mill at Green River was built in 1957 by the Union Carbide Corporation, which operated the mill from 1958 until 1961. During its 3 years of milling operations, 166 014 t (183 000 tons) of ore from the uranium mines at Temple Mountain, Utah, were upgraded. This ore averaged 0.29% uranium oxide. The upgraded ‘ore concentrate’ was shipped by rail to Rifle, Colorado (another designated UMTRA site), for further processing.

Remaining at the designated site were 3.23 ha (8 acres) of tailings pile containing 87 159 m³ (114 000 yd³) of tailings, several mill buildings and a water tower. Additional contaminated wind-blown and subpile materials brought the total volume of contaminated materials to be remediated to 141 595 m³ (185 200 yd³). Seventeen vicinity properties were also identified for remediation.

The Green River residual radioactive materials were stabilized on-site, which involved relocating the materials to an area 183 m (600 ft) south of the mill site. The remedial action project was completed in September 1989. The buildings and facilities were decontaminated and left intact. The final 3.64 ha (9 acres) of restricted disposal cell area are owned and maintained by the DOE. The remaining 18.2 ha (45 acres) are fenced and owned by the State of Utah. This land will eventually be released for any use consistent with existing land use controls such as a light industrial area. The environmental assessment²⁵ on the remedial actions contains addi-

tional details on the proposed actions and alternatives, as well as a description of the environment and impacts. The DOE is currently preparing a long term surveillance plan for the Green River site as part of licensing.

(7) MINE

There were no mines associated with the Green River UMTRA Project site.

(8) MILL

(a) Type/size: The ore was sandstone loosely cemented with clay and asphaltic material, with part of the uranium intimately associated with the carbonaceous material. After crushing and grinding, the ore was screened and processed by flotation to form a carbonaceous concentrate. The flotation tailings were separated into sand and slime fractions. The sands were leached with acid, the leached slurry washed and the spent sands discarded to the tailings area. The recovered slimes and pregnant solution were then joined with a portion of the initial slime fraction. Any excess acid was neutralized with ammonia. The mixed product and the remainder of the primary slimes were then dewatered and dried for rail shipment to the Rifle, Colorado, plant for further processing.

(b) Grade milled: The overall mill rate averaged 0.29% uranium oxide. A total of 166,014 t (183,000 tons) of ore was processed.

(c) Method of decommissioning: The office, mill and crusher building were decontaminated, restored and renovated. The roaster and utility buildings were demolished and the demolition debris placed in the disposal cell.

(d) Cost of decommissioning: The total cost of remedial action, including completion of regulatory requirements, decontamination and demolition activities at the mill site, relocation of the tailings and other residual radioactive materials to the disposal cell, licensing of the disposal site, and remediation of the Green River related vicinity properties, is estimated at US $14,614,648.

(e) Surface and groundwater controls: After the completion of remedial action, the mill site disturbed areas were backfilled with uncontaminated fill, regraded to promote surface drainage, reseeded, gullies were filled and the floodplain of Brown's Wash regraded. Groundwater controls and restoration will be addressed during the upcoming groundwater restoration phase of the UMTRA Project.
(f) **Monitoring and institutional control requirements:** Interim groundwater monitoring will continue at the mill site until the groundwater restoration planning phase of the UMTRA Project commences. The mill site is owned/fenced by the State of Utah. Access is restricted.

(9) **TAILINGS IMPOUNDMENT(S) AND WASTE TREATMENT FACILITIES**

(a) **Type of impoundment:** Tailings pile.

(b) **Quantity and surface area:** An estimated 124,283.66 t (137,000 tons) of tailings were generated from the 166,014 t (183,000 tons) of ore processed over the mill’s 3 year life span; however, over half of the tailings were washed down Brown’s Wash to the Green River in a flash flood in 1959. Approximately 103,418 m$^3$ (114,000 yd$^3$) contained in a roughly rectangular pile that covered 3.24 ha (8 acres) were remediated.

(c) **Activity and physical characteristics:** The tailing are finely ground white to pink sands with a bulk density of 1476.6 kg/m$^3$ (92 lb/ft$^3$). About 85% of the total radioactivity originally in the uranium ore remained in the tailings after processing. Site radiological characterization indicated that $^{226}$Ra concentrations in the tailings were 3.6 Bq/g (98 pCi/g). A radon flux ranging from 1.2 to 4.8 Bq·m$^{-2}$·s$^{-1}$ (tailings covered with up to 15 cm of material, various states of erosion) is indicated in Table III of IAEA Technical Reports Series No. 335 [3].

(d) **Non-radiological contaminants:** Barium, lead, selenium, arsenic and vanadium.

(e) **Method of decommissioning:** The plan was stabilization on-site, which required relocation of the tailings to a disposal site approximately 183 m (600 ft) to the southeast of the original tailings pile location adjacent to the mill. After remedial action was completed, the site was inspected by the DOE and the NRC for compliance with the requirements of UMTRA.

(f) **Cover characteristics:** All the contaminated materials were covered by a multicomponent cover design to minimize infiltration. The cover contains the following layers, starting with the layer directly above the contaminated materials (Figs A–6 and A–7).

   (i) **Infiltration/radon barrier:** This is 91 cm (36 inches) thick and is composed of compacted silty clay. It was designed to protect the groundwater by
FIG. A-6. Diagrammatic cross-section of disposal cell and foundation, Green River, Utah, disposal site.
FIG. A-7. Disposal cell cover system, Green River, Utah, tailings site (see Fig. A-6 for location of this detail in relation to the disposal cell). ($K_{sat}$ = saturated hydraulic conductivity.)
minimizing infiltration and to reduce the radon flux. Six per cent bentonite by weight was mixed into the radon barrier material to ensure that the compacted infiltration/radon barrier has a saturated hydraulic conductivity of less than $2 \times 10^{-8}$ cm/s. Approximately 53 cm (21 inches) of the infiltration/radon barrier are below the maximum projected frost depth of 99 cm (39 inches) at the toe of the sideslopes.

(ii) **Bedding layer:** This is a 15.24 cm (6 inch) layer to prevent migration of the infiltration/radon barrier into the overlying riprap erosion protection layer.

(iii) **Rock erosion protection layer:** This is designed to protect the disposal cell from runoff, flooding and encroachment of gullies. The uppermost portion of the erosion protection barrier is a 0.3 m (12 inch) thick layer of 2.54–10.16 cm (1–4 inch) riprap (Type A). Around the toe of the pile, a 91.44 cm (36 inch) thick apron of 25.4–76.2 cm (10–30 inch) riprap (Type B) was placed below ground. A 0.3 m (12 inch) thick layer of riprap (Type A) and a 15.24 cm (6 inch) layer of bedding material were placed between the Type B riprap and the underlying infiltration/radon barrier to prevent migration of the finer materials into the Type B riprap.

(g) **Cost of decommissioning:** The estimated cost of remedial action at the Green River site is presented in (d) in item (8). Given the integrated nature of the UMTRA Project remedial action activities at each site, it is difficult to separate out the cost of remediating just the tailings.

(h) **Surface and groundwater controls:** The disposal cell was sited on a terrace 22.5 m (75 ft) above the channel and floodplain of Brown's Wash to avoid the problem of channel migration over time. The riprap toe protection extends 6 m (20 ft) on the surface from the disposal cell to reduce erosion of the ground surface adjacent to the cell. Existing gullies near the cell were regraded and filled to minimize the erosion potential and the formation of new gullies. The area around the disposal cell was graded to promote sheet flow and to reduce flow concentrations that might cause gully erosion. The infiltration/radon barrier was constructed of compacted silty clay, and was designed to protect groundwater by promoting runoff and minimizing infiltration. Also, the DOE estimated the groundwater travel time from the top of the buffer layer in the disposal unit to the water table beneath the site. Disposal cell design features, such as cover construction, siting in an arid climate, limiting the tailings placement moisture content to prevent construction water drainage, including an underlying buffer layer to absorb exiting contaminants, are intended to prevent the introduction of contaminants into groundwater by providing for leachate travel times from the base of the cell to groundwater in excess of the design life (1000 years) of the cell. Hazardous constituent concentrations in groundwater at and beyond the point of compliance (POC), the northwestern and
FIG. A-8. Compliance monitoring well system, Green River, Utah, disposal site.
FIG. A-10. Final site conditions, Green River, Utah, disposal site.
northeastern edges of the engineered cell, will not increase above the EPA's prescribed concentration limits as a result of releases from the disposal cell for at least 1000 years after completion of the remedial action. About 18 m (60 ft) of riprap and select fill lie between the compacted tailings and the POC.

(i) **Monitoring and institutional control requirements:** No erosion control monitoring features are required, beyond the periodic surveillance and maintenance inspections that would normally include checking for any developing erosion features. Should gullies nearing 2.1 m (7 ft) in depth measured at the apron approach towards the disposal cell, a Phase II follow-up inspection will be scheduled to analyse the situation and to determine the appropriate course of action. There are seven POC and four upgradient (background) wells for monitoring the two middle hydrostratigraphical units. The DOE will sample these wells quarterly for a 2 year interim period following completion of remedial action, quarterly for another year, semi-annually for years 2 to 6, and annually thereafter (Fig. A–8). The State of Utah acquired the designated mill site and the surrounding land; a permanent fence surrounds the land owned by the State of Utah. Upon completion of remedial action, the State of Utah will transfer title of the disposal site to the Federal Government. Much of the land immediately adjacent to the disposal site is leased by the Federal Government and access is restricted. After completion of the remedial actions, the Green River disposal site will be permanently retained and maintained by the DOE (or another Federal agency) under the conditions established in a general licence to be issued by the NRC. The disposal cell will be restricted from unauthorized entry and public use, except for the disposition of subsurface mineral rights by sale or lease under Section 104(h) of UMTRA, provided that the cell is not disturbed by these activities. Survey and boundary monuments, site markers and perimeter warning signs are permanent surveillance and maintenance features at the unfenced disposal site. The perimeter sign at the entrance to the site also displays the name of the site, and the names and telephone numbers of the DOE and the Utah Department of Health, Bureau of Radiation Control (Figs A–9 and A–10).

(10) **MINING DEBRIS PILES**

There were no waste rock (debris) piles associated with the Green River UMTRA Project.

(11) **HEAP LEACH PILES**

There were no heap leach piles associated with the Green River UMTRA Project.
(12) VICINITY PROPERTY REMEDIATION

(a) **Type of remediation:** There were 17 vicinity properties cleaned up as part of the remediation project: six were commercial properties, seven residential properties and four vacant lot properties. A total of 34 417 m$^3$ (45 016 yd$^3$) of material was removed, and 85 m$^3$ (111 yd$^3$) were left in place at one vicinity property through the application of supplemental standards.

(b) **Removal or cover of material:** Exterior remedial work was performed on all 17 properties. Contaminated materials were removed, topsoil replaced in some situations and the properties restored to their prior uses.

(c) **Remediation:** The contaminated vicinity property materials were placed in the Green River disposal cell.

(d) **Cost:** The estimated cost of remedial action at the 17 Green River vicinity properties is US $1 545 742.

(e) **Monitoring and institutional control requirements:** Property records are generally annotated to note the remediation of vicinity properties, or the refusal of the property owner to allow remediation of identified contaminated materials. Normally, no other monitoring or controls are required.
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[31] UNITED STATES NUCLEAR REGULATORY COMMISSION, Guidelines for Decontamination of Facilities and Equipment Prior to Release for Unrestricted Use or Termination of Licenses for Byproduct, Source or Special Nuclear Material, NRC, Washington, DC (1982).


[54] UNITED STATES CODE OF FEDERAL REGULATIONS, Title 10, Part 50, Annex B, CFR, Washington, DC.

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Operating Experience


Monitoring for Compliance with Cleanup Criteria


analysis, cost-benefit. A systematic economic evaluation of the positive effects (benefits) and negative effects of undertaking an action. Cost-benefit analysis may be used for optimization studies in radiation protection evaluations.

barrier. A physical obstruction that prevents or delays the movement (e.g. migration) of radionuclides or other material between components in a system, e.g. a waste repository. In general, a barrier can be an engineered barrier which is constructed or a natural barrier which is inherent to the environment of the repository.

clay. Minerals that are essentially hydrated aluminium silicates or occasionally hydrated magnesium silicates, with sodium, calcium, potassium and magnesium cations. Also denotes a natural material with plastic properties which is essentially a composition of fine to very fine clay particles. Clays differ greatly mineralogically and chemically and consequently in their physical properties. Because of their large surface areas, most of them have good sorption characteristics.

closeout. In the context of uranium mill tailings impoundments, the operational, regulatory and administrative actions required to place a tailings impoundment into long term conditions such that little or no future surveillance and maintenance are required. The same concept may apply to mining debris piles, heap and in situ leaching piles, and mines.

criteria. Conditions on which a decision or judgement can be based. They may be qualitative or quantitative and should result from established principles and standards. In radioactive waste management, criteria and requirements are set by a regulatory body and may result from specific application of a more general principle.

critical group. For a given radiation source and given exposure pathway, a group of members of the public whose exposure is reasonably homogeneous and is typical of individuals receiving the highest dose through the given pathway from the given source.

decommissioning. Actions taken at the end of the useful life of a nuclear facility in retiring it from service with adequate regard to the health and safety of workers and members of the public and protection of the environment. The ultimate goal of decommissioning is unrestricted release or use of the site. The time period to achieve this goal may range from a few to several hundred years. Subject to legal and regulatory requirements of a Member State, a

1 Definitions from the Radioactive Waste Management Glossary, 3rd edn (Dec. 1993) have been adopted.
nuclear facility or its remaining parts may also be considered decommissioned if it is incorporated into a new or existing facility, or even if the site in which it is located is still under regulatory or institutional control. This definition does not apply to some nuclear facilities used for mining and milling of radioactive materials (closeout) or for the disposal of radioactive waste (closure).

decontamination. The removal or reduction of radioactive contamination by a physical and/or chemical process.

design life. The period during which a facility and its components are expected to perform according to the technical specifications to which they will be or were engineered.

disposal. The emplacement of waste in an approved, specified facility (e.g. near surface or geological repository) without the intention of retrieval. Disposal may also include the approved direct discharge of effluents (e.g. liquid and gaseous wastes) into the environment with subsequent dispersion.

effluent. Gaseous or liquid radioactive materials which are discharged into the environment.

emanation. Release of radioactive gas formed by decay of a radioactive solid. The emanation may or may not be retained within the pore space of the solid phase in which it was formed.

embankment. A raised structure usually constructed as an earthen dam to retain liquid and solid wastes. These structures are used in the management of mining and mill tailings. The embankment may be built using tailings and/or other materials.

groundwater. That part of subsurface water that is in the saturated zone, including underground streams. The term excludes water of hydration. Groundwater can be brought to the surface by pumping.

heap leaching. In mining and milling, the process whereby leach liquor percolates through a pile of mined ore placed on an impervious base in such a way that the leachate can be collected for recovery of the metal values.

in situ leaching. In mining and milling, the process whereby leach liquor percolates through or is injected into the ore body in such a way that the leachate can be collected for recovery of the metal values.

institutional control. Control of a waste site (e.g. disposal site, decommissioning site, etc.) by an authority or institution designated under the laws of a country or state. This control may be active (monitoring, surveillance, remedial work) or passive (land use control) and may be a factor in the design of a nuclear facility (e.g. near surface disposal facility).

liner. A layer of clay, plaster, asphalt or other impermeable material placed around or beneath a tailings impoundment to prevent leakage and/or erosion. (See also tailings impoundment.)

milling. The operation of processing ore to extract uranium or thorium for conversion into reactor fuel.
mining debris. Debris (usually rock) generated by mining activities which does not have a sufficient uranium or thorium content to be useful as ore.

monitoring. The measurement of radiation or radionuclides for reasons related to the assessment or control of exposure and the interpretation of such measurements. Monitoring can be continuous or non-continuous.

ore. A mineral or rock containing an element and/or compound in a quantity and of a quality so as to make mining and extraction of the element and/or compound economically or otherwise viable.

radioactive waste management. (See waste management, radioactive.)

regulatory authority. (See regulatory body.)

regulatory body. An authority or a system of authorities designated by the government of a country or state as having legal authority for conducting the licensing process, for issuing licences and thereby for regulating the siting, design, construction, commissioning, operation, closure, closeout, decommissioning and, if required, subsequent institutional control of the nuclear facilities (e.g. near surface repository) or specific aspects thereof. This authority could be a body (existing or to be established) in the field of nuclear related health and safety, mining safety or environmental protection vested and empowered with such legal authority.

remedial action. Action taken to reduce a radiation dose that might otherwise be received in an intervention situation involving chronic exposure, when a specified action level is exceeded. Examples are: (a) Actions which include decontamination, waste removal and environmental restoration of a site during decommissioning and/or closeout efforts. (b) Actions taken beyond stabilization of tailings impoundments to allow for other uses of the area or to restore the area to near pristine conditions.

residues. All solids and associated liquids resulting from ore mining and milling to recover uranium and other minerals.

restricted release or use. A designation, by the regulatory body in a country or state, to restrict the release or use of equipment, materials, buildings or the site because of its potential radiological hazards.

rock mulch. In mining and milling, a mixture of broken rock and soil materials, which is randomly spread on a surface to resist erosion. It should resist normal forces from rainfall and wind but is not intended to resist concentrated water flows. In many cases vegetation will develop over a rock mulch, which should aid against erosion.

site. The area containing, or under investigation for its suitability to construct, a nuclear facility (e.g. a repository). It is defined by a boundary and is under effective control of the operating organization.

storage (interim). The placement of waste in a nuclear facility where isolation, environmental protection and human control (e.g. monitoring) are provided
with the intent that the waste will be retrieved for exemption or processing and/or disposal at a later time.

**subsidence.** The settling of the Earth’s surface as a result of applied loads or by consolidation of underlying layers. Such consolidation may result from the removal of water within the soils or as a result of changed drainage or water obstruction.

**tailings.** (a) Mill tailings, which are the residues resulting from processing the ore in a mill to extract the metal values. (b) Heap leach residues, which result from treatment of ore by heap leaching.

**tailings impoundment.** A structure in which the tailings and tailings solution are deposited, including all its elements such as embankment walls, liners and cover layers.

**tailings pile.** A deposit of tailings material.

**tailings stabilization.** In the context of mill tailings impoundment, the actions needed to physically and chemically stabilize the tailings and the containment barriers. Such actions may include dewatering the tailings, building/repairing the dams and covering the tailings.

**unrestricted release or use.** A designation, by the regulatory body in a country or state, that enables the release or use of equipment, materials, buildings or the site without radiological restriction.

**vicinity property.** An area or structure which exhibits some level of contamination because of the presence of materials from a uranium mine or mill. This material may have resulted from a wind-blown or water-borne process or may have arisen from human relocation. A vicinity property is usually not in the ownership of the mine or mill owner or operator.

**waste.** (See waste, radioactive.)

**waste, radioactive.** For legal and regulatory purposes, radioactive waste may be defined as material that contains or is contaminated with radionuclides at concentrations or activities greater than clearance levels as established by the regulatory body, and for which no use is foreseen. (It should be recognized that this definition is purely for regulatory purposes, and that material with activity concentrations equal to or less than clearance levels is radioactive from a physical viewpoint — although the associated radiological hazards are negligible.)

**waste management, radioactive.** All activities, administrative and operational, that are involved in the handling, pretreatment, treatment, conditioning, transportation, storage and disposal of waste from a nuclear facility.

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2 In the context of this Glossary, the term ‘waste’ refers to radioactive waste, unless otherwise specified.
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