Safe Management of Wastes from the Mining and Milling of Uranium and Thorium Ores

CODE OF PRACTICE AND GUIDE TO THE CODE
CATEGORIES OF IAEA SAFETY SERIES

From 1978 onwards the various publications in the Safety Series are divided into four categories, as follows:

1) IAEA Safety Standards. Publications in this category comprise the Agency’s safety standards as defined in “The Agency’s Safety Standards and Measures”, approved by the Agency’s Board of Governors on 25 February 1976 and set forth in IAEA document INFCIRC/18/Rev. 1. They are issued under the authority of the Board of Governors, and are mandatory for the Agency’s own operations and for Agency-assisted operations. Such standards comprise the Agency’s basic safety standards, the Agency’s specialized regulations and the Agency’s codes of practice. The covers are distinguished by the wide red band on the lower half.

2) IAEA Safety Guides. As stated in IAEA document INFCIRC/18/Rev. 1, referred to above, IAEA Safety Guides supplement IAEA Safety Standards and recommend a procedure or procedures that might be followed in implementing them. They are issued under the authority of the Director General of the Agency. The covers are distinguished by the wide green band on the lower half.

3) Recommendations. Publications in this category, containing general recommendations on safety practices, are issued under the authority of the Director General of the Agency. The covers are distinguished by the wide brown band on the lower half.

4) Procedures and Data. Publications in this category contain information on procedures, techniques and criteria pertaining to safety matters. They are issued under the authority of the Director General of the Agency. The covers are distinguished by the wide blue band on the lower half.

Note: The covers of publications brought out within the framework of the NUSS (Nuclear Safety Standards) Programme are distinguished by the wide yellow band on the upper half.
SAFE MANAGEMENT OF WASTES FROM THE MINING AND MILLING OF URANIUM AND THORIUM ORES
The following States are Members of the International Atomic Energy Agency:

<table>
<thead>
<tr>
<th>Afghanistan</th>
<th>Guatemala</th>
<th>Paraguay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albania</td>
<td>Haiti</td>
<td>Peru</td>
</tr>
<tr>
<td>Algeria</td>
<td>Holy See</td>
<td>Philippines</td>
</tr>
<tr>
<td>Argentina</td>
<td>Hungary</td>
<td>Poland</td>
</tr>
<tr>
<td>Australia</td>
<td>Iceland</td>
<td>Portugal</td>
</tr>
<tr>
<td>Austria</td>
<td>India</td>
<td>Qatar</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>Indonesia</td>
<td>Romania</td>
</tr>
<tr>
<td>Belgium</td>
<td>Iran, Islamic Republic of</td>
<td>Saudi Arabia</td>
</tr>
<tr>
<td>Bolivia</td>
<td>Iraq</td>
<td>Senegal</td>
</tr>
<tr>
<td>Brazil</td>
<td>Ireland</td>
<td>Sierra Leone</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>Israel</td>
<td>Singapore</td>
</tr>
<tr>
<td>Burma</td>
<td>Italy</td>
<td>South Africa</td>
</tr>
<tr>
<td>Byelorussian Soviet Socialist Republic</td>
<td>Jamaica</td>
<td>Spain</td>
</tr>
<tr>
<td>Cameroon</td>
<td>Japan</td>
<td>Sri Lanka</td>
</tr>
<tr>
<td>Canada</td>
<td>Jordan</td>
<td>Sudan</td>
</tr>
<tr>
<td>Chile</td>
<td>Kenya</td>
<td>Sweden</td>
</tr>
<tr>
<td>China</td>
<td>Korea, Republic of</td>
<td>Switzerland</td>
</tr>
<tr>
<td>Colombia</td>
<td>Kuwait</td>
<td>Syrian Arab Republic</td>
</tr>
<tr>
<td>Costa Rica</td>
<td>Lebanon</td>
<td>Thailand</td>
</tr>
<tr>
<td>Cote d'Ivoire</td>
<td>Liberia</td>
<td>Tunesia</td>
</tr>
<tr>
<td>Cuba</td>
<td>Libyan Arab Jamahiriya</td>
<td>Turkey</td>
</tr>
<tr>
<td>Cyprus</td>
<td>Liechtenstein</td>
<td>Uganda</td>
</tr>
<tr>
<td>Czechoslovakia</td>
<td>Luxembourg</td>
<td>Ukrainian Soviet Socialist Republic</td>
</tr>
<tr>
<td>Democratic Kampuchea</td>
<td>Malaysia</td>
<td>Union of Soviet Socialist Republic</td>
</tr>
<tr>
<td>Democratic People's Republic of Korea</td>
<td>Mali</td>
<td>United Arab Emirates</td>
</tr>
<tr>
<td>Denmark</td>
<td>Mauritius</td>
<td>United Kingdom of Great Britain and Northern Ireland</td>
</tr>
<tr>
<td>Dominican Republic</td>
<td>Mexico</td>
<td>Ireland</td>
</tr>
<tr>
<td>Ecuador</td>
<td>Monaco</td>
<td>United Republic of Tanzania</td>
</tr>
<tr>
<td>Egypt</td>
<td>Morocco</td>
<td>United States of America</td>
</tr>
<tr>
<td>El Salvador</td>
<td>Namibia</td>
<td>Uruguay</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>Netherlands</td>
<td>Venezuela</td>
</tr>
<tr>
<td>Finland</td>
<td>New Zealand</td>
<td>Viet Nam</td>
</tr>
<tr>
<td>France</td>
<td>Nicaragua</td>
<td>Yugoslavia</td>
</tr>
<tr>
<td>Gabon</td>
<td>Niger</td>
<td>Zaire</td>
</tr>
<tr>
<td>German Democratic Republic</td>
<td>Nigeria</td>
<td>Zambia</td>
</tr>
<tr>
<td>Germany, Federal Republic of</td>
<td>Norway</td>
<td></td>
</tr>
<tr>
<td>Ghana</td>
<td>Pakistan</td>
<td></td>
</tr>
<tr>
<td>Greece</td>
<td>Panama</td>
<td></td>
</tr>
</tbody>
</table>

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

© IAEA, 1987

Permission to reproduce or translate the information contained in this publication may be obtained by writing to the International Atomic Energy Agency, Wagramerstrasse 5, P.O.Box 100, A-1400 Vienna, Austria.

Printed by the IAEA in Austria
June 1987
SAFETY SERIES No. 85

SAFE MANAGEMENT OF WASTES FROM THE MINING AND MILLING OF URANIUM AND THORIUM ORES

CODE OF PRACTICE
and
GUIDE TO THE CODE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1987
FOREWORD

Nuclear power is making a significant contribution to energy supply in many countries. Appropriate solutions to the management of wastes resulting from nuclear power and its fuel cycle are necessary. From its inception the IAEA has been active in the field of radioactive waste management. Considerations for the proper management of wastes from the mining and milling of uranium and thorium ores were first set out by the IAEA in 1976 in Safety Series No. 44, Management of Wastes from the Mining and Milling of Uranium and Thorium Ores — A Code of Practice and Guide to the Code. A technical report describing current practices and options for confinement of uranium mill tailings was published by the IAEA in 1981 (Technical Reports Series No. 209).

Since the publication of the above reports, there have been a number of developments affecting both the technical and regulatory aspects of the management of these wastes, which have necessitated this update of IAEA Safety Series No. 44. A first draft of the report was prepared in a consultants meeting in 1983, and was revised in two Advisory Group meetings in 1983 and 1984. The report was finalized by incorporation of comments received from the members of the Advisory Groups by consultants in two meetings held in 1984 and 1985. Its completion also involved consideration of comments from national and other authorities.

This document consists of two parts: a Code of Practice (Part I) and a Guide to the Code (Part II). For ease of reference they are sometimes referred to in the text as ‘the Code’ and ‘the Guide’. The Code sets forth the requirements for the safe and responsible handling of the wastes resulting from the mining and milling of uranium and thorium ores (sometimes referred to in the text simply as ‘radioactive ores’), while the Guide presents further guidance in the use of the Code together with some discussion of the technology and concepts involved.
This publication is no longer valid
Please see http://www.ns-iaea.org/standards/
This publication is no longer valid
Please see http://www.ns-iaea.org/standards/

CONTENTS

Part 1. CODE OF PRACTICE

1. INTRODUCTION .............................................................. 1
2. OBJECTIVE ................................................................. 2
3. SCOPE ............................................................................... 2
4. DEFINITIONS ...................................................................... 3
5. WASTES FROM THE MINING AND MILLING OF RADIOACTIVE ORES, THEIR RADIOLOGICAL IMPACT AND CONTROL BY WASTE MANAGEMENT ......................................................... 7
6. PRINCIPLES OF RADIOLOGICAL PROTECTION .............. 8
7. RESPONSIBILITIES .......................................................... 9
8. DESIGN OF WASTE MANAGEMENT FACILITIES ............. 9
9. COLLECTION, STORAGE AND TREATMENT OF WASTES .... 10
10. OPERATION OF WASTE MANAGEMENT FACILITIES ........ 10
11. DECOMMISSIONING OF MINES, MILLS AND WASTE MANAGEMENT FACILITIES ......................................................... 10
12. MONITORING, SURVEILLANCE AND MAINTENANCE ....... 11

Part 2. GUIDE TO THE CODE

1. INTRODUCTION .............................................................. 12
2. OBJECTIVE ................................................................. 12
3. SCOPE ............................................................................... 12
4. DEFINITIONS ...................................................................... 13
5. WASTES FROM THE MINING AND MILLING OF RADIOACTIVE ORES, THEIR RADIOLOGICAL IMPACT AND CONTROL BY WASTE MANAGEMENT ......................................................... 13
6. PRINCIPLES OF RADIOLOGICAL PROTECTION ........................................ 17
   6.1. Introduction ................................................................. 17
   6.2. General ........................................................................ 18
   6.3. Justification of the practice ........................................... 18
   6.4. Optimization of radiation protection ............................... 19
       6.4.1. Differential cost-benefit analysis ........................... 20
       6.4.2. Multi-attribute analysis ....................................... 23
   6.5. Individual dose limitation ............................................. 24
7. RESPONSIBILITIES ..................................................................... 26
   7.1. Responsibilities of the owner/operator/manager ............... 26
   7.2. Responsibilities of the competent authority ..................... 28
   7.3. General ......................................................................... 29
8. DESIGN OF WASTE MANAGEMENT FACILITIES ........................... 30
   8.1. Design objectives .......................................................... 30
   8.2. Site selection ............................................................... 30
       8.2.1. Climate and meteorology ...................................... 31
       8.2.2. Geography, geomorphology, demography and land use 32
       8.2.3. Geology and seismicity ......................................... 32
       8.2.4. Geochemistry ....................................................... 32
       8.2.5. Mineralogy ............................................................ 32
       8.2.6. Hydrology and flooding ....................................... 33
       8.2.7. Flora and fauna .................................................... 33
   8.3. Environmental impact assessment .................................... 34
   8.4. Design considerations ................................................... 34
9. COLLECTION, STORAGE AND TREATMENT OF WASTES ............ 36
   9.1. Mine wastes ................................................................. 36
       9.1.1. Exploration wastes .............................................. 36
       9.1.2. Operational wastes .............................................. 37
       9.1.3. Liquid wastes ...................................................... 38
       9.1.4. Airborne wastes .................................................. 41
       9.1.5. In situ leaching wastes ......................................... 41
   9.2. Mill wastes ................................................................. 42
       9.2.1. Solid wastes ....................................................... 42
       9.2.2. Liquid wastes ...................................................... 46
       9.2.3. Airborne wastes .................................................. 49
10. OPERATION OF WASTE MANAGEMENT FACILITIES .................. 50
11. DECOMMISSIONING OF MINES, MILLS AND WASTE MANAGEMENT FACILITIES ......................................................... 52
   11.1. Mine ........................................................................... 53
       11.1.1. Underground mines ............................................ 53
2. OBJECTIVE

The objective of this Code of Practice is to set forth basic requirements for the management of wastes produced from the mining and milling of uranium and thorium ores. These, supplemented by more specific and quantitative requirements established by the competent authority, are designed to ensure that any radiological detriments to humans and their environment will be limited as required in the recommendations of ICRP [2] as implemented by the Basic Safety Standards for Radiation Protection [1].

3. SCOPE

This Code of Practice together with the Guide to the Code are intended for the use of those involved in either the regulation or the management of wastes produced from the mining and milling of uranium and thorium ores. Its recommendations may also be of use to those mining and milling other ores which incidentally contain uranium and thorium and in other operations which produce wastes that may contain small but non-trivial amounts of radioactive material such as brown coal ash, mineral sands wastes, or by-product gypsum and phosphate residues. Others people, including members of the public, may find the document useful as a general reference.

The Code is directed primarily towards mining and milling operations related to the recovery of uranium. Because most of the mining and milling of radioactive ore up to this time has been for uranium rather than thorium, this Code and the Guide are based upon this experience and upon the isotopes present in the uranium decay series. Nevertheless, the general approach contained in the documents is applicable to and provides guidance for management of wastes from the mining and milling of thorium and thorium bearing ores.

The Code includes requirements for the management and control of solid, liquid and airborne wastes, the decommissioning and rehabilitation of mines, mills and related waste management facilities, and, as required, their subsequent surveillance and maintenance. The Code does not address the control of exposure of workers in mining and milling operations, which is discussed in IAEA Safety Series No. 26, Radiation Protection of Workers in the Mining and Milling of Radioactive Ores [8], and further in the IAEA report on the Application of the Dose Limitation System to the Mining and Milling of Radioactive Ores [9]. Reference [10] provides a general review of long term issues and impacts associated with non-radiological contaminants in uranium mill tailings.

Although the wastes resulting from the mining and milling of radioactive ores contain potentially hazardous non-radioactive as well as radioactive components, the Code and the Guide address primarily the management of the radioactive components of the waste. Further, it should be noted that internationally established
requirements for the non-radioactive components of the waste do not exist. Thus, the
competent authority should establish its own requirements as needed.

It is recommended that the Code be applied to existing and proposed waste
management operations and, with due regard to what is judged reasonable, to
abandoned facilities.

4. DEFINITIONS

The following definitions are included to assure proper understanding and
interpretation of the key terms used in the Code and the Guide. Many of the terms
have been defined in a sense relating specifically to the context of the mining and
milling of radioactive ores; others in the sense in which they are commonly used in
the nuclear waste management field.

ALARA. An acronym for "as low as reasonably achievable", a concept meaning
that the design and use of sources, and the practices associated with them,
should be such as to ensure that exposures are kept as low as reasonably prac­
ticable, economic and social factors being taken into account.

barren solution. Acid or alkaline liquor from which the recoverable uranium
(and/or thorium, where applicable) has been removed. This solution often
contains re-usable reagents.

collective effective dose equivalent. For a given source, the integrated product of
effective dose equivalent and number of individuals in the population:

\[ S_E = \int_{H_E=0}^{H_E=\infty} H_E P(H_E) \, dH_E \]

where \( P(H_E) \, dH_E \) is the number of individuals receiving an effective dose
equivalent between \( H_E \) and \( H_E + dH_E \) from the given source. The unit is the
man-•-sievert.

collective effective dose equivalent commitment. For any specified event, decision
or defined finite portion of a practice, the infinite time integral of the collective
effective dose equivalent rate as a function of time, \( \dot{S}_E(t) \), caused by that
event, decision or defined finite practice:

\[ S_{E,C} = \int_{t=0}^{t=\infty} \dot{S}_E(t) \, dt \]
$S_{E,C}$ is commonly expressed in units of man-sievert. The collective effective dose equivalent commitment according to the ICRP recommendations is assumed to be proportional to the total health detriment from a source or practice provided that all individual doses are in the range where only stochastic effects are relevant.

**Collective Effective Dose Equivalent Rate.** The integrated product of the effective dose equivalent rate and the number of individuals in the population:

$$\dot{S}_E = \int_0^\infty H_E \ P(\dot{H}_E) \ d\dot{H}_E$$

where $P(\dot{H}_E) \ d\dot{H}_E$ is the number of individuals receiving an effective dose equivalent rate between $H_E$ and $H_E \pm dH_E$. The total collective effective dose equivalent rate from a given source is obtained by including all individuals irradiated from the source and is a function of time.

**Competent Authority.** An authority designated or otherwise recognized by a government for specific purposes, in connection with radiation protection and/or nuclear safety, in this case the protection of man and the environment from any adverse effects of the activities of the mine, mill and associated waste management facilities.

**Conditioning of Waste.** Those operations that transform waste into a form suitable for transport and/or storage and/or disposal. The operations may include converting the waste to another form, enclosing the waste in containers, and providing additional packing.

**Containment of Waste.** The retention of radioactive material in such a way that it is effectively prevented from becoming dispersed into the environment or is only released at an acceptable rate.

**Controlled Release.** Deliberate release of radioactive materials into the environment, using techniques and limits approved by the competent authority.

**Cost–Benefit Analysis, Differential.** A procedure for optimization of radiation protection used to determine the point at which exposures have been decreased so far that any further decrease is considered less important than the additional necessary effort required to achieve it.

**Decommissioning.** The work required for the planned permanent retirement of a nuclear facility; in this case a uranium or thorium mine, mill or waste management facility (or parts thereof) from active service.

**Detriment.** The mathematical expectation of the harm (damage to health and other effects) incurred from the exposure of individuals or groups of persons in a
human population to a radiation source, taking into account not only the probabi­
lities but also the severity of each type of deleterious effect.

disposal. The emplacement of waste in a repository, or at a given location, without
the intention of retrieval. Disposal also covers the approved direct discharge
of wastes into the environment.

dose. A term used in radiation protection with two meanings:
   (i) a measure of the 'quantity of radiation' present in, or 'given' by a
       radiation field — a concept now known as 'exposure', and
   (ii) a measure of the radiation 'received' or 'absorbed' by a target.

effluent. A fluid (liquid or gas) which is released into the environment. This fluid
may contain solids.

embankment. A raised structure constructed to retain wastes.

gangue minerals. The worthless rock or vein matter in which valuable metals or
minerals occur.

heap leaching. The process whereby leach liquor percolates through a pile of mined
ore in such a way that the leachate can be collected for recovery of the metal
values.

in situ leaching. 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 by an authority or institution designated under the
laws of a country or state. This control may be active (monitoring, surveil­
lance, remedial work) or passive (land use control).

manager. A duly qualified and appointed person responsible for the administration
and direction of the mine and/or mill and associated waste management
facility.

mill tailings (tailings). Finely ground residues resulting from the processing of ore
for recovery of uranium and thorium. Uranium mill tailings consist of two
major fractions:
   (a) slimes — the lighter, finer particles in the tailings (including particles in
       the micron and submicron range) made up of the clays and other very
       fine particles;
   (b) sands — the heavier, coarser range of particles.

monitoring. The measurement of radiation or activity for reasons related to the
assessment or control of exposure to radiation or radioactive material, and the
interpretation of such measurements.
operator. Any person, government or other entity that conducts or carries on operations for the mining and/or milling of uranium and thorium ores.

optimization (of radiation protection). See ALARA and cost–benefit analysis, differential.

ore. A mineral or chemical aggregate 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.

owner. Any person, government or other entity that holds title to or owns the mining, milling and waste management facilities and/or the land on which these facilities are located.

primary treatment facility. A facility intended for the deposition and retention of tailings and storage of contaminated liquids for the purposes of clarification and evaporation.

sands. See mill tailings

secondary treatment facility. A facility intended for additional treatment of wastes beyond that provided for by primary treatment. Secondary treatment facilities commonly consist of mechanical and/or chemical treatment systems.

slimes. See mill tailings.

stabilization. A general term indicating any of various possible actions for rendering tailings or other wastes more resistant to dispersion by natural, or other, forces.

stochastic event. A random event which can be predicted only by the probability of its occurrence.

storage. The emplacement of wastes in a facility with the intent that they will be retrieved at a later time.

surveillance. All planned activities performed to ensure compliance with operational specifications established for a particular installation.

tailings impoundment system. A system designed specifically for the storage or disposal of mill tailings.

waste concentrates. The product resulting from treatment performed to separate and/or concentrate certain components from the bulk of the wastes.

waste management facility. The systems for receiving, transporting, treating, processing, storing or disposing of wastes resulting from a uranium or thorium mine/mill facility.
waste management. All activities, administrative and operational, that are involved in the handling, treatment, conditioning, transportation, storage and disposal of wastes.

waste retention system. A system for storage or disposal of liquid and/or solid wastes generated by the uranium or thorium mining and milling process.

waste rock. Rock generated by mining activities which does not have a sufficient uranium or thorium content to be useful as ore.

5. WASTES FROM THE MINING AND MILLING OF RADIOACTIVE ORES, THEIR RADIOLOGICAL IMPACT AND CONTROL BY WASTE MANAGEMENT

Most wastes from the mining and milling of radioactive ores are to some extent radioactive, and are thus potential sources of radiological impact, both for those working in the industry and for members of the public who may be exposed if wastes are dispersed in the environment. Such potential radiological impacts are assessed both in terms of dose to individuals and consequent individual risk, and in terms of collective dose and consequent detriment (see Section 6).

Wastes from the mining and milling of radioactive ores include solids and liquids. The process also produces airborne effluents containing radioactive gases and particulates. Prior to operation each step in the overall process (exploration, mining, milling and decommissioning) shall be examined, the wastes arising identified and the radiological consequences assessed. During mining and milling the liquid and airborne effluents may be the major sources of radiological impact requiring control, but following cessation of operations the mill tailings present the major source of potential radiological impact, since they are present in large quantities and contain most of the radionuclides from the uranium or thorium decay chains present in the original ore. Radon and its daughters may be released from the tailings and dispersed in the atmosphere and radium and other radionuclides may enter surface or groundwater, augmenting naturally occurring levels in the environment of these radionuclides, and associated risks and detriments.

During operation, measures shall be taken to limit the rates of release of contaminants in liquid and airborne effluents to the environment. Such measures should ensure that solid wastes remain under proper control so that misuse of tailings is avoided and releases of radon or radioactive dusts to the atmosphere and of radium and other radionuclides to surface or groundwater by surface runoff or leaching from the solid wastes are controlled. Following cessation of operations the solid wastes shall receive continued attention as required to ensure control of releases to the atmosphere or to surface or groundwater, and to ensure the prevention of misuse of the wastes and the possibility of human intrusion. The degree of control required will
be determined using the provisions of Section 6 of this Code, together with the requirements of the competent authority.

Because of the long half-lives of the radionuclides involved, consideration shall be given to the long term impact of environmental processes (erosion, floods, drainage diversion or meander of watercourses, seismicity, etc.) on the design options for controlling releases from the final disposal site.

The selection of the design option for a particular waste management facility shall be agreed upon between the owner/operator/manager and the competent authority, which implies the need for timely co-operation between them.

6. PRINCIPLES OF RADIOLOGICAL PROTECTION

The Basic Safety Standards for Radiation Protection [1] apply to new or existing sources or practices involving exposure to ionizing radiation subject to control by the competent authority. They are based on the system of dose limitation recommended by the ICRP [2], which comprises three principles; justification, optimization and individual dose limitation. These principles are expressed in the Basic Safety Standards [1] as follows:

— JUSTIFICATION OF A PRACTICE: In order to prevent unnecessary exposure, no practice involving exposure to ionizing radiation shall be authorized by the relevant competent authorities unless the introduction of the practice produces a positive net benefit.

— OPTIMIZATION OF RADIATION PROTECTION: The design, plan and subsequent use and operation of sources and practices shall be performed in a manner to ensure that exposures are as low as reasonably achievable, economic and social factors being taken into account.

— INDIVIDUAL DOSE LIMITATION: No individual shall be exposed, as a result of controlled sources and practices, in excess of the recommended limits.

The basic requirement of this Code is compliance with the Basic Safety Standards [1]. However, it is recognized that some expansion of the basic principles for radiation protection outlined above is required in assessing the control necessary for the radiological hazards from radioactive waste disposal. Guidance on these aspects is given in the Guide to the Code based on the work of an NEA expert group [5] and the ICRP [6]. For normal operations, guidance on the application of these principles in limiting the release of radioactive effluents into the environment is given in Ref. [11].
7. RESPONSIBILITIES

The organizational, structural and associated responsibilities for waste management may vary considerably from country to country, but the basic approaches and structures adopted shall be capable of ensuring that the following basic responsibilities of the owner/operator/manager and of the competent authority can and will be effectively carried out.

— The owner/operator/manager shall present to the competent authority for approval his plans for waste management intended to ensure compliance with the requirements of this Code and review of all the evidence required to demonstrate compliance with those plans.

— The competent authority is responsible for the timely review and the approval of the submitted plans, and the audit of the evidence of compliance presented by the owner/operator/manager.

The Guide to the Code contains a listing of specific items which should be considered by the owner/operator/manager and the competent authority in accordance with the above.

8. DESIGN OF WASTE MANAGEMENT FACILITIES

The design of a waste management facility shall be such as to assure compliance with the requirements of this Code and the further conditions and limits established by the competent authority.

Proper design must include:

(a) Subject to economic and practical constraints, the selection of a suitable site taking optimum advantage of desirable characteristics. Factors to be considered in site selection include: climate, meteorology, hydrology and flooding, geography, geomorphology, geology, seismicity, mineralogy, geochemistry, demography and land use, flora and fauna, and amenability to decommissioning and permanent disposal of the wastes.

(b) Completion of an environmental impact statement assessing, through appropriate site specific analysis and modelling, the projected impact of the sited facility on the environment, including estimates of present and future individual and collective dose rates.

(c) Consideration of appropriate measures for optimizing protection in order to limit individual doses and reduce collective doses, including such factors as minimization of exposed tailings surfaces, adequacy of confinement systems over the operational life of the facility and beyond, seepage control, and plans for eventual decommissioning.
In order for the design to be acceptable, the assessment must demonstrate with a reasonable degree of certainty that the impact of the proposed facility on the environment and human health and safety will be acceptable to the competent authority.

9. COLLECTION, STORAGE AND TREATMENT OF WASTES

Plans and procedures for the waste management facilities required for the collection, transportation, treatment, storage and eventual disposal of all wastes shall be formulated in advance of operation and approved by the competent authority prior to implementation.

All wastes produced during exploration, construction, mining, milling and waste management shall be collected and managed in such a way as to assure that the requirements of this Code and the site specific requirements of the competent authority are met.

10. OPERATION OF WASTE MANAGEMENT FACILITIES

The operation of waste management facilities shall be performed in accordance with the design objectives of the owner/operator/manager and the requirements of the competent authority and shall include provision for:

— manuals for operation, maintenance and monitoring;
— adequate training of personnel for operation, maintenance and monitoring;
— adequate surveillance and maintenance of all system components including a quality assurance programme and restrictions, as necessary, on access to and/or removal of materials from the site;
— submissions required by the competent authority, including inspection reports, monitoring results and reports on unusual occurrences.

11. DECOMMISSIONING OF MINES, MILLS AND WASTE MANAGEMENT FACILITIES

At the end of the useful life of a mine, mill or waste management facility, health, safety and environmental considerations require that certain actions be taken to decommission such facilities. The required actions shall be those necessary to ensure that the facilities are kept in a safe and stable condition and that releases of radioactive and other contaminants are as low as reasonably achievable and within regulatory limits. A decommissioning plan shall be proposed for each facility on site and approved by the competent authority before construction of that facility. This
decommissioning plan should be revised regularly through the operating life of the facility and the revisions approved by the competent authority.

The decommissioning plans shall comply with the requirements of the competent authority and address:

- the safety of abandoned buildings and mine workings;
- decontamination to acceptable levels of areas not utilized for disposal;
- disposal of contaminants and contaminated materials;
- stabilization of waste rock piles, heap leach sites and tailings impoundments.

12. MONITORING, SURVEILLANCE AND MAINTENANCE

The goals of pre-operational, operational and post-operational monitoring and surveillance are:

- to determine whether there is compliance with the regulations and procedures of the competent authority;
- to provide data from which individual and collective dose rates resulting from the facility may be assessed;
- to check the effectiveness of engineering and process designs and technical solutions, and the models employed for the design;
- to indicate whether or not discharge authorizations should be redefined;
- to trigger special inspections if needed;
- to identify unexpected environmental contamination and transfer routes and pathways;
- to check the physical condition and integrity of the waste management facilities so that repairs can be effected if needed; and
- to collect data for information and advice to the public if necessary.

The monitoring, surveillance and maintenance of a waste management facility shall be performed in such a way as to ensure compliance with the requirements of this Code and those established by the competent authority. These functions shall continue throughout the period of operation and decommissioning, and to the extent and for the duration specified by the competent authority, after decommissioning.

The owner/operator/manager shall provide adequate monitoring, surveillance and maintenance personnel and equipment to meet the above requirements during the period for which he is responsible for the facility. Making arrangements for the continuation of these functions upon the termination of the responsibility of the owner/operator/manager shall be the responsibility of the competent authority.
Part II

GUIDE TO THE CODE

1. INTRODUCTION

The Guide to the Code explains the principles and concepts presented in the Code. The wastes arising from the mining and milling of uranium and thorium ores are described and their associated hazards are discussed. The influence of environmental considerations on the management of the wastes is outlined. Guidance is given for applying the principles of radiological protection. Current practice in the design, operation and decommissioning of waste management facilities is described. A compendium of experience and developments in the management of wastes from uranium mining and milling can be obtained from the proceedings of the IAEA symposium held in 1982 [12]. For ease of reference the sections of the Guide correspond directly to those in the Code.

2. OBJECTIVE

The aim of the Guide to the Code is to assist persons responsible for implementing the Code, in conformance with the requirements of the competent authority, by making available the experience of those who have been involved in establishing the basic requirements for the management of wastes and in implementing these requirements.

3. SCOPE

Both the Code and the Guide have been written to be sufficiently general to be useful in all situations involving uranium and thorium mining and milling, and in an even more general way for thorium and other mining and milling operations which involve these materials as wastes. It must be recognized, however, that there is no such thing as a typical mine or mill or a typical environmental setting. For this reason, site specific requirements will have to be established or approved by the competent authority, taking into account the material presented in the Guide.

The Code and the Guide address primarily the management of wastes from the mining and milling of uranium because the mining and milling of thorium have been of only limited scope. However, thorium has sometimes been recovered as a by-product of uranium mining. Thorium, occurring in the mineral monazite, is also often recovered in connection with the mining of rutile, zircon and ilmenite from
beach sand or placer deposits. The mining of mineral sands does not have a great deal in common with uranium mining operations. Uranium ore is usually extracted using hard rock mining methods, the ore being crushed, milled and then chemically treated to obtain a uranium concentrate which is essentially free of decay products since they are discharged with the mill tailings. Mineral sand mining for thorium on the other hand involves physical processes to concentrate the heavy minerals present in unconsolidated sands. Hard rock mining methods are not needed to extract mineral sands. Grinding and chemical treatment are, however, required in treating the concentrated heavy minerals to separate thorium and its compounds. Wastes from thorium operations pose radiological problems and the requirements of the Code and recommendations of the Guide are generally applicable.

Much of the material in the Guide to the Code should be useful in the management and handling of wastes from other operations which involve naturally occurring radioactive materials. Such radioactive materials usually occur in low concentrations, but often in very large volumes in materials such as brown coal ash and by-product gypsum or phosphate residues. The use of such wastes for fill or other construction related purposes can create problems similar to those associated with uranium mill tailings, and therefore warrants some degree of management.

Reference is made in the Code to its application to abandoned facilities. It should be recognized that many now-abandoned facilities were active many years ago when practices were different and environmental awareness was not prevalent. The competent authority will have to assess what is reasonable in these cases and apply the Code and Guide accordingly.

4. DEFINITIONS

The definitions selected to aid in the understanding of both the Code and the Guide to the Code are presented in Section 4 of the Code.

5. WASTES FROM THE MINING AND MILLING OF RADIOACTIVE ORES, THEIR RADIOLOGICAL IMPACT AND CONTROL BY WASTE MANAGEMENT

Uranium and thorium mining and milling produce large quantities of solid and liquid wastes as well as airborne contaminants which are identified in Section 9. The radionuclides giving rise to the radiological hazards associated with these wastes are those resulting from the uranium-238 and thorium-232 decay series. These are illustrated in Fig. 1 [13]. Several points may be noted in connection with this chart:

In uranium mining and processing, uranium-238 is the parent nuclide of principal concern because of its relative abundance and because of certain radionuclides mentioned below which appear exclusively in its decay series.
FIG. 1. Potential radioactive contaminants in uranium mill tailings.
Most of the radioactivity present in the ore is discharged with the mill tailings. Radium-226 is the nuclide of principal concern from the standpoint of the assessment and control of the radiological hazard associated with the mill tailings; it may be present at an average concentration in the range of 10–1000 kBq/kg depending on the grade of the ore.

Because of the long half-lives of the radionuclides involved, their potential impact will extend far into the future. The rate of decay of thorium-230, with a half-life of 80 000 a, will determine the level of radioactivity for a few hundred thousand years. Subsequently, the rate of decay will be governed by the residual uranium-238, half-life 4.5 x 10^9 a, present in the wastes. However the concentration of uranium in the tailings is much lower than in the original ore.

Radium-226, with a half-life of 1600 a, decays to radon-222. Radon-222 is a noble gas which exhales from wastes into the atmosphere or into buildings located on or near the wastes. Radon-222 in turn decays with a half-life of 3.8 d, giving rise to several short lived daughters.

The dispersion of radon from a tailings pile and the inhalation of radon and its decay products by persons living in the vicinity by the aerial route increases the risk of lung cancer in the recipients. It is the most serious potential health hazard resulting from these wastes, particularly if the tailings are misused as building material or fill; radon and its decay products can accumulate to substantial levels inside structures built on radium containing fill or built of radium containing material.

The total radon exhalation from tailings and waste rock is dependent on many factors, such as; the method of waste management, the amount of waste, the concentration of radium-226, the fraction of radon produced that escapes into the interstitial pore spaces, the rate of diffusion of the radon through the bulk solids, moisture content, precipitation and temperature.

Windborne dust containing radionuclides is generated from dry surfaces and can contribute to off-site exposure. This will be of concern to people living near the vicinity of tailings piles. Studies of wind patterns and the mechanism of dust transport are important for assessment of this problem.

Mill tailings are usually conveyed from the mill to the tailings impoundment as a slurry and may contain large quantities of liquid. Unless controlled, the liquids can be transported through runoff or seepage into local surface or groundwater systems. Leaching of radium-226 from tailings to surface or groundwaters is a recognized exposure route in some circumstances and should therefore also be considered. Leached radium-226 is a source of lead-210 and polonium-210 in the environment; the latter may contribute more to collective dose rates than the radium itself.

The natural thorium decay series also contains an isotope of radon, radon-220. As its half-life is only 55 s, most of the radon-220 produced in thorium bearing
wastes decays in situ, and little escapes to the atmosphere. Exposures to airborne radon-220 and its daughter products from thorium wastes are thus generally not significant. The wastes may, however, be a significant source of local gamma radiation exposure from the 2.6 MeV gamma ray emitted by the polonium-212 in the thorium decay chain. Thorium bearing wastes must therefore be disposed of with sufficient care to reduce gamma radiation exposure rates to levels approved by the competent authority.

Additional data and discussion of the characteristics of the radionuclides in the natural uranium and thorium decay series may be found in Refs [4, 13, 14].

To assess the radiological impact of uranium and thorium mining and milling, it is necessary to give careful consideration to the sources and exposure pathways associated with transport of radon and thoron gases, and particulate material containing uranium and thorium and their decay products and leached radionuclides. The potential sources of radioactivity of sufficient magnitude to warrant consideration are:

— Underground mine ventilation discharges, opencut mining activities such as blasting;
— The initial stages of milling, including ore storage, conveyance, crushing and leaching;
— The final stage of product preparation including drying and packaging; and
— The mill tailings and other waste residues from the operations.

The principal pathways through which released radioactivity may reach humans are:

— Direct, external exposure to gamma rays from radionuclides in the air or on the ground;
— Inhalation of radioactivity into the lungs, possibly followed by redistribution to other organs of the body; and
— Ingestion of radioactive materials in foodstuffs and drinking water.

Past and current experience suggests that the local and regional collective dose commitments from the mining and milling of radioactive ores depend primarily upon the airborne releases which contribute to external exposure from deposited material and to internal irradiation via the inhalation and ingestion pathways. However, because of low release rates and extended dispersion, the resulting individual dose rates at some distance, say beyond 1 km, from the source will be very small, typically less than 10 μSv·a⁻¹. These contributions are similar for uranium and thorium mining and processing.

At short distances from the source the individual dose rates are highly dependent upon local, site specific factors. Annual effective dose equivalents from several microsieverts to a few hundred microsieverts have been estimated at the site boundary for typical mine/mill/waste management facilities. It may be noted that at
a short distance from the source the dose from the milling of thorium is generally greater than that for uranium.

Even though the annual individual doses to the public from mining and milling wastes are small, they contribute the major part of the collective radiological impact of the nuclear fuel cycle [4]. Also, it may be noted that because of the low release rates and the extended dispersion of radon and its decay products in the atmosphere, the resulting individual doses will be very small, and it has been estimated that individual doses less than 1 μSv·a⁻¹ may contribute more than 90% of the collective dose.

6. PRINCIPLES OF RADIOLOGICAL PROTECTION

6.1. Introduction

The wastes from the mining and milling of radioactive ores contain non-radioactive as well as radioactive constituents. Both may be potentially hazardous.

This section of the Guide deals only with the control of hazards from the radioactive constituent, and is concerned with the protection of members of the public from the wastes. It gives details of cost–benefit analysis as suggested in the Basic Safety Standards [1]. An alternative qualitative approach, multi-attribute analysis, is also discussed [5].

It is recognized that there are difficulties in the application of the Basic Safety Standards due to the characteristics of the wastes from mining and milling of radioactive ores. These arise from the large volumes of the wastes, potential wide dispersion and the long half-lives of some of the radioactive constituents. The Basic Safety Standards were prepared mainly with exposure from more conventional radiation sources in mind, i.e. they apply particularly to the control of exposures which are certain to occur within a fairly short time frame. In the case of mining and milling wastes, there is also a need to consider exposures which may or may not occur, for example exposure due to human intrusion into the wastes at some future time. In these respects the problems are similar to those encountered in developing a radiation protection philosophy appropriate to other types of solid radioactive waste disposal. Recent publications by NEA [5] and ICRP [6] address these issues, but further guidance and clarification are still needed on the principles and methods to achieve acceptable radiation protection in relation to mining and milling wastes. Further discussion on the subject is required at national and international levels.
6.2. General

The objectives of radiation protection are the prevention of the occurrence of non-stochastic effects, and the limitation of the probability of occurrence of stochastic effects (risk) to levels deemed to be acceptable. The Basic Safety Standards adopt the system of dose limitation recommended by the ICRP, comprising the three principles of justification, optimization and individual dose limitation as described in Section 6 of the Code.

A salient feature of these principles is that they not only require the limitation of individual dose but also introduce source related requirements.

The source related requirements (justification and optimization) stem from the following assumptions and considerations:

(a) Any level of dose results in a probability of stochastic effects (malignancies and genetic effects) in the exposed population, and, therefore, at any reasonable level of protection applied to the source there is an expectation of harm caused by the source. Non-stochastic effects are not relevant in these considerations because they are not present at doses and dose rates less than individual dose limits.

(b) The radiation detriment due to a source relates to all human radiation exposures, both present and future, caused by the source during its lifetime. Under the linearity assumption, the expected number of stochastic effects is proportional to the collective effective dose commitment from the source.

(c) Any level of protection applied to the source involves an effort and an associated cost, which diverts resources from other beneficial uses.

(d) Conceptually there is an optimum level of protection for a given source which minimizes the combination of protection efforts and cost, and the radiation detriment from the source. This optimum level of protection should be adopted if it is lower than that required by the third principle of radiation protection, i.e. the individual dose limit, but should not be adopted if it is higher than this value.

For normal operations, the principles for limiting releases of radioactive effluents into the environment, and the application of these principles in the case of mining and milling of radioactive ores are given in Ref. [11]. These reports contain relevant information on the procedures for setting release limits including optimization of release control, and the main factors to be taken into consideration for optimization of radiation protection and individual dose limitation. Examples of the application of these principles are given in Refs [5, 7].

6.3. Justification of the practice

The justification of a proposed practice or operation involving exposure to radiation could be ascertained by consideration of all the expected advantages and
disadvantages, to ensure that there will be an overall net benefit from the introduction of the practice. The competent authority or an appropriate governmental body needs to ensure that the benefit expected from a proposed practice is larger than the total detriment.

Ideally a cost–benefit analysis could be used for making this type of basic policy decision. In practice, however, the identification and evaluation of all the terms, as would be required in an absolute assessment of justification, is a complex and difficult undertaking. Additionally, the existence of many intangible costs and benefits introduces the need for value judgements in attempting to quantify many of the items involved in the analysis.

The mining and milling of uranium ores is part of the nuclear fuel cycle, and thus involved in the supply of energy to society. The management of the wastes produced cannot, therefore, be viewed in isolation. Rather, in justifying the generation of electricity by nuclear fission, the impacts of the wastes generated must be taken into account. The justification thus depends on a positive net benefit of nuclear power production. In some countries radioactive ores are mined and milled not for use in nuclear power generation within that country but for export sales. In this case the justification of the practice will involve the comparison of the detriments with the benefits to the national economy.

Guidance on the assessment of the benefits of mining and milling of radioactive ores within a given economic system is outside the scope of this document and will generally be performed independently of the assessment of the associated detriments.

The role of radiation protection in justification procedures is to ensure that the radiation detriment is adequately addressed and is taken into consideration in the decision making process. The assessment of the radiation detriment resulting from the mining and milling of radioactive ores for purposes of the justification of the practice has much in common with the assessment of this detriment for the purpose of optimizing radiation protection, and is further discussed in Section 6.4.1.

6.4. Optimization of radiation protection

Two important approaches to the optimization of radiation protection are presented in this section. The first approach is that of differential cost–benefit analysis. The basic methodology is presented in the Basic Safety Standards [1] and is discussed in more detail in the NEA and ICRP publications [5, 7, 15]. A number of problem areas arise in quantifying the parameters involved in the analysis and in projecting their behaviour over the long periods of time associated with the wastes from the mining and milling of radioactive ores. While it is considered useful and instructive to carry through such an analysis, the results may not indicate a clear choice of options, and for this reason alternative approaches should also be considered. One such alternative is the method of multi-attribute analysis, which is the approach presented in Section 6.4.2.
Use of optimization methods should aid the choice between various control options. Of the available options, only those can be considered which result in acceptably low individual doses. The criterion for judging what is acceptably low can be derived by reference to the basic dose limit. However, since that limit is individual related, irrespective of source, account must be taken of the presence of other sources, the continued operation of all these sources in the future, and the eventual introduction of new sources. For this reason a source related limit, lower than the dose limit and called the source upper bound, must be set by the competent authority as the boundary condition for optimizing [5, 11].

6.4.1. Differential cost–benefit analysis

This approach to the optimization of radiation protection consists of an analysis in which the level of protection is increased incrementally, thus incrementally reducing the radiation detriment, to a value such that further reductions in the detriment are less significant than the additional efforts required to achieve such reductions. Expressed mathematically this involves defining and estimating the costs of a range of protection options, such that the interplay between the cost of protection and cost of the associated detriment complies with the relation

\[ X(w) + Y(w) = \text{minimum} \]

where \( X \) is the cost of protection, and \( Y \) is the cost of the radiation detriment, both at a level of protection represented by \( w \) (e.g. tailings cover thickness, alternative options for protection of groundwater, etc.). It should be noted that \( w, X(w) \) and \( Y(w) \) can in some cases be continuous variables, while in other cases they take only discrete values.

These optimization assessments require dimensional compatibility between cost of protection and cost of detriment. Usually for solving this compatibility problem both the cost of protection and the cost of radiological detriment are expressed in monetary units. As the radiological detriment is proportional to the collective effective dose equivalent commitment \( (S_{E,C}) \), this proportionality may then be represented by a dimensional term \( \alpha \) and the problem reduces to the assignment of a monetary value to this term. It must be realized that this assignment is a social value judgement, rather than a scientific determination, reflecting how much a society is willing to pay to prevent a statistical deleterious effect. Generally this value will be established by the competent authority or some other governmental body. In the absence of an established value, a value, or range of values, may be assumed for the purpose of carrying out the analysis.

Distributional problems occur when people receiving the detriment from the practice would not receive the benefit in equal degree. This problem of costs, detriments, and benefits distributed over different populations at different times is
complex, at least from an ethical viewpoint. It can also involve political and legal complexities. How this problem affects the value of $\alpha$ can best be judged on a national basis. However, a uniform approach requires that the value of $\alpha$ used in optimization should be applied to all collective doses. The value for collective doses appearing in the distant future may not be a problem in the case of optimization, because in practice the long term contributions to collective dose commitments from the various options under consideration may be identical and cancel out in the comparisons [15].

In cases where dispersed radionuclides cross national boundaries, the value of $\alpha$ used should not be lower, when applied to the other countries, than the value applied within the source country and should not be lower than an internationally agreed value [16].

In many practical cases of optimization, the changes in protection levels are achieved in finite increments, both $X$ and $S_{E,C}$ being discrete instead of continuous variables. The decision to go from a level of protection $A$, represented by a certain design option, to a more expensive level of control $B$, represented by a different design option, would be taken if

$$- \frac{X_B - X_A}{S_{E,C_B} - S_{E,C_A}} \leq \alpha$$

The optimization assessment in this case consists of a step by step procedure that has to be verified to ensure that at a given apparent optimum no additional step would make the ratio $- \Delta X/\Delta S_{E,C}$ approach more closely the value of $\alpha$.

This same approach may be applied to subsystems within the total system, provided the subsystems are independent in the sense that the protection in one of them does not influence the collective effective dose equivalent commitment from the others. Thus, in the case of independent subsystems, optimization of protection can be obtained by optimizing each independent subsystem separately. Similarly, the optimization for the combined exposures from several installations at a given site can be obtained by optimizing separately the protection at each installation, provided the condition of independence applies.

Further discussion and illustration of the application of the differential cost-benefit technique are available in the following sources:

— Basic Safety Standards, Annex IV, sections 200 and 206-216, provides a more detailed mathematical development of the technique [1].
— The NEA report on Long-Term Radiological Aspects of the Management of Wastes from Uranium Mining and Milling [7], in which the cost-benefit approach is applied on a case study basis to actual or model situations in Australia, Canada and the United States of America. These case studies illustrate the problems encountered in the application of the approach, and some
FIG. 2. Example of hierarchy of factors for evaluation of waste management systems by multi-attribute analysis [5].
of the simplifying steps which can be taken to keep the scope of the analysis within practical and manageable limits.

The NEA report on the Long-Term Radiation Protection Objectives for Radioactive Waste Disposal [5] provides further guidance on the estimation and use of collective dose commitment. In particular, the report addresses the issue of truncation of the integration of collective dose in time as a means of addressing the problems inherent in attempting to integrate to infinity. Considering the increasing uncertainties in the far future, periods of a few thousands of years are thought to be the upper limit for any realistic consideration in connection with optimization.

6.4.2. Multi-attribute analysis

This technique may be useful if the differential cost-benefit analysis does not lead to a clear choice of options. Also by permitting the consideration of certain intangibles which are not treated in the cost-benefit analysis, it represents an approach that may be useful and advantageous in its own right. This technique has been described by Watson and Hayward [17, 18] and Fourcade and Zettwoog [19]. The following is an extract from an NEA report [5] which summarizes the technique.

"The objective of this technique is to construct a scoring system for alternatives, with the property that the alternative with the highest score is preferred. The first step is to structure the problem. It is necessary to identify all the factors which distinguish between the alternatives under consideration. However, only the most significant ones need be retained in the further steps of the decision-making process. The outcome of structuring the problem is a hierarchy of attributes, in which some factors are treated separately and some are grouped together. An example is shown in Figure 2 [see Fig. 2 of present report]. Radiological impact has a number of attributes which can be separately valued, but it aids comparisons between alternatives to group them together. This structuring exercise is valuable in itself in promoting openness in decision-making and in providing a framework for the assessment of alternatives.

The second stage is to structure the preferences for each factor in a formal way. It is necessary to construct a measurement scale such that the preferences between different values of an attribute are represented by values on a common scale. Preferences are usually those of a group of individuals who have the responsibility for taking decisions in the public interest. When independent factors are considered, mutual preference independence ensures that the weight given to one factor does not vary when the levels of other attributes are changed. It is in addition necessary that a given increment in score for each attribute is equivalent no matter at what point on the scale the increment arises;
for example an increment from 40 to 50 points in the valuation of radiation protection preference must mean the same as an increment from 70 to 80 points. Once a measurement procedure for each attribute is agreed, it is necessary to ensure that the weights applied to these value fractions reflect the judgements on balances of preference between attributes. This will inevitably be subjective and approximate, but use of multi-attribute analysis can make a valuable contribution by focussing discussion on real differences between opinions and by identifying central issues. Since it does not involve expression of all the factors in terms of a common denominator (e.g. monetary value), multi-attribute analysis, in principle, is capable of dealing with all relevant factors.”

6.5. Individual dose limitation

As a limiting condition for the optimization of radiation protection the Code requires that individual doses shall be below limits established by the competent authority. These limits are intended to limit the individual risk to an acceptable level. They apply to the sum of doses from all sources of radiation except natural background and medical exposures. The limits presented in the Basic Safety Standards [1] are:

— “The limit for the annual effective dose equivalent for members of the public is 5 mSv. The annual dose equivalent limit for the individual organs and tissues of members of the public is 50 mSv. These dose limits are to be applied to the critical group of the population.

— When the same individual members of the public could otherwise be exposed at or near the annual effective dose equivalent limit for prolonged periods (many years) it would be prudent to take measures to restrict their lifetime effective dose equivalent to a value corresponding to an annual average of 1 mSv.”

The ICRP now takes the view [20] that the principal limit for members of the public is 1 mSv in a year, but that it is permissible to use a subsidiary dose limit of 5 mSv in a year for some years, provided that the average annual effective dose equivalent over a lifetime does not exceed the principal limit of 1 mSv in a year. This change is also reflected in Ref. [11].

The individual exposure varies greatly among groups of people and among individuals in a group depending on such things as distance from the source, prevailing weather conditions, environmental factors and living habits of the individuals. Apart from exposed workers, there is among the exposed groups of people a group of individuals who on average will receive higher doses than others. This group, which is called the critical group, should be identified and the limitation of releases and other protective measures should be made on the basis of the estimated average exposure of this group.
The critical group is most often found in the neighbourhood of the source facility and parameters typical for this environment should be determined and used in the assessment of the exposure of the critical group. Then a screening analysis of the pathways should be undertaken. All major pathways of the radionuclides and ways of exposure should be considered and judged so as to get a complete understanding of the resulting exposures.

Because of the practical difficulties and limitations in making measurements and performing experimental investigations prior to the commencement of the actual operations, it is necessary to estimate the correlation between releases and doses to people on the basis of modelling. The appropriate choice of models and data requires judgement; an attempt should be made to make cautious but reasonable assumptions. As the practice goes on, environmental measurements should be performed to improve the models and strengthen the reliability of the assessments of the relationships between release and dose rate.

Because of the long half-lives of the nuclides in the uranium and thorium decay series, the potential environmental impact of waste disposal will persist, and hence needs control beyond the normal human concern for the future. For the accurate assessment of doses to a critical group in the long term, it is necessary to make realistic assumptions concerning future demography, land use and the habits and diets of people. The uncertainties associated with projections of these parameters in the long term may result in large errors. These errors could lead to either an over-estimation or underestimation of individual doses to the critical group. The collective dose could be affected similarly. Consequently, it is necessary for the competent authority to make judgements as to assumptions to be used in estimating future doses to critical groups and on the time periods over which these assumptions are appropriate. Truncation may be considered when analysis of options shows that beyond some point in time a component of collective dose is common to all options. These aspects are developed more fully in Refs [5, 6].

As mentioned in Section 6.4, account has also to be taken of the existence of other sources of radiation besides the source under consideration both at the present time and in the future for the same critical group, and it is therefore necessary to partition the basic dose limit to make allowance for these additional sources to which an individual may be exposed. The competent authority is responsible for establishing the fraction of the basic individual dose limit appropriate for the source or practice under consideration (the source upper bound) [5, 11].

The above consideration of doses to the critical group is based on a single judgement of the most probable scenario of future events and their resulting environmental impacts. However, there might be other scenarios with lower probabilities of occurrence, for example exposures resulting from accidental or deliberate intrusions into the wastes, giving rise to larger individual doses. This can be incorporated into the analysis if considered in conjunction with the probability of the dose being
received, as follows. With a single scenario a chosen option is acceptable if the maximum individual dose in the future does not exceed a given limit, say \( X \, \text{mSv} \cdot \text{a}^{-1} \). That means that we today will not intentionally expose anyone in the future to a higher risk than that corresponding to \( X \, \text{mSv} \cdot \text{a}^{-1} \), even if we do not know when exactly this will occur. An alternative scenario with a dose consequence of \( 10X \, \text{mSv} \cdot \text{a}^{-1} \), but a probability of occurrence of 0.1 during the same time of interest, has the same probability of harm as the dose rate of \( X \, \text{mSv} \cdot \text{a}^{-1} \) with unit probability of occurrence. In terms of probability of harm to individuals the two scenarios are equivalent. This equivalence may be extended by interpreting the individual dose limit as an individual risk limit and requiring that the sum of risks over a number of conceivable scenarios be limited appropriately. These ideas are discussed in Ref. [5] and developed further by ICRP [6].

7. RESPONSIBILITIES

This section sets out a recommended list of the specific responsibilities of the owner/operator/manager of a uranium or thorium mine, mill and waste management facility, and of the competent authority.

7.1. Responsibilities of the owner/operator/manager

The owner/operator/manager is responsible for:

1. Documentation to be submitted to the competent authority for approval before commencing or recommencing any waste management operations:

   a. The proposed programme of baseline monitoring and operational and post-operational studies of environmental impact. Guidance on the preparation of environmental impact assessments is available in Refs [21, 22].

   b. The proposed set of assumptions and methods to be used for assessing the radiological impacts of proposed operational and post-operational discharges and releases of radionuclides to the environment from the waste generated by the mining and milling operation.

   c. The technical and administrative proposals to be adopted for the control and limitation of discharges. The proposals should cover all phases of the mining and milling operation, including:
      - exploration of an identified or suspected radioactive ore deposit;
      - development of the mine and design and construction of the mill and any associated waste management facility;
— operation of the mine and mill and any associated waste management facility;
— decommissioning of the mine or mill or any associated waste management facility; and
— the post-decommissioning situation.

The proposals should include descriptions of the techniques and administrative requirements to be adopted to ensure that individuals do not receive doses from released radionuclides in excess of the appropriate authorized limits and that doses are kept as low as reasonably achievable, economic and social factors being taken into account.

(d) The programmes and methods proposed for measuring and assessing releases of contaminants to the environment, and where required by the competent authority a proposal for authorized release limits. The objectives and design of environmental monitoring programmes for radioactive contaminants are given in Refs [23-25].

(e) The proposed quality assurance programme.

(f) The evaluation of the probabilities and consequences of unplanned events which may result in unacceptable impact on the environment. In studying potential unplanned events, it may be possible to implement design or operational changes that would significantly reduce the possibility or severity of such events.

(g) The proposed contingency plans for remedial action to mitigate the consequences of unplanned events.

(h) Proposed financial arrangements and responsibilities for ensuring that there are funds to carry out decommissioning activities and post-decommissioning maintenance and monitoring.

(2) The implementation as approved of the programmes outlined in item 1, recording of the results and making them available to the competent authority.

(3) Ensuring that the measurements and assessments of releases are used in a manner approved by the competent authority to update the assumptions and methods used to assess environmental impacts.

(4) Periodical review and updating, during the life of the operation, of the waste management programmes and facilities, including operation and maintenance manuals.

(5) Notification to the competent authority of any circumstance or condition which may require, or is likely to require, a departure from a previously approved system or programme, and obtaining approval from the competent authority to amend the system or programme accordingly.
(6) Informing anyone purchasing land determined by the competent authority to be affected by the waste from the mining and milling of uranium and thorium ores of the nature of the wastes and the applicable requirements of the Code, and informing the competent authority of the proposed transaction.

(7) Affording the competent authority, at any reasonable time, the right of access and opportunity to examine equipment, working procedures and records to be kept by the owner/operator/manager as required by the competent authority.

(8) Informing the competent authority promptly of any failure by the owner to comply with the terms of any approval.

(9) The employment of sufficient staff, with qualifications and experience acceptable to the competent authority, and providing them with adequate and suitable equipment and facilities to establish, operate and maintain the systems and programmes, including training programmes approved by the competent authority.

(10) The performance in a manner approved by the competent authority of all work undertaken by contractors retained by the owner/operator/manager.

7.2. Responsibilities of the competent authority

The competent authority is responsible for:

(1) Reviewing in a timely manner submissions by the owner/operator/manager related to the management of wastes from the mining and milling of uranium and thorium ores and authorizing the approved plans for implementation.

(2) Reviewing in a timely manner submissions by the owner/operator/manager related to decommissioning of a uranium or thorium mine, mill and associated waste management facilities and authorizing the approved plans for implementation.

(3) Inspecting the operation, systems, programmes, proposals and records to ensure that the owner/operator/manager is complying with the terms and conditions specified in the approvals.

(4) Investigating failures of compliance with approvals as reported by the owner/operator/manager, or determined by inspection, and directing the owner/operator/manager to undertake actions to limit the consequences of the event or failure and to prevent recurrences.

(5) Where judged necessary, carrying out its own monitoring to confirm the records of the owner/operator/manager.
Determining or approving authorized release limits for contaminants discharged to the environment. Principles for limiting the release of radioactive effluents into the environment are discussed in Ref. [11].

Ensuring that such arrangements are made for inspection, monitoring and, as necessary, maintenance of decommissioned mines, mills and waste disposal sites as are necessary to meet the intent of the Code.

To the extent possible, ensuring that financial arrangements are made for adequate decommissioning of a uranium or thorium mine, mill and associated waste management facility and for post-decommissioning monitoring and maintenance as necessary.

7.3. General

It is essential to the achievement of their common goal, the safe and economical management of wastes, that the relationship between the competent authority and the operating organization be based on mutual understanding and respect. Consequently, the operating organization should regard the competent authority as a valuable source of constructive criticism and technical advice, and the latter should maintain a high level of understanding of the technical and economic problems of the operating organization.

In preparing contingency plans for remedial action to mitigate the consequences of unplanned events, several such events should be studied and their potential effects assessed. In general, the only unplanned event that may have more than transitory radiological effects is a large release of tailings or waste concentrate resulting from radical failure of the tailings impoundment. As such failures have occurred, it appears advisable to make prior evaluation of the potential consequences and to have emergency response plans ready for implementation to limit the effects.

When a transfer of ownership takes place for land which is determined by the competent authority to be affected by wastes from the mining and milling of uranium and thorium ores, it is important that the new owner is informed of the nature of the wastes and of any restriction to the use of the land. The competent authority should also be informed of the purchase. When ownership of the land is changed, it shall be ensured that the future obligations for monitoring and maintenance of the land are fulfilled. It can be considered that these obligations should “run with the land”, such that upon a change in the ownership of the land, the new owner would incur the obligations. Mechanisms should be established to ensure that encumbrances on the land are made known to any prospective purchaser.
8. DESIGN OF WASTE MANAGEMENT FACILITIES

8.1. Design objectives

Basic design and operating objectives for waste management facilities are in all cases:

— to control the present and future releases of radioactive contaminants to the environment in accordance with the requirements of Section 6 of the Code and of the competent authority;
— to control the present and future releases of non-radioactive contaminants to the environment in accordance with the requirements of the competent authority;
— to provide waste management facilities which are both physically and chemically stable;
— to enable effective decommissioning.

The desired approach is an iterative process involving the consideration of various sites and appropriate designs to meet the above objectives.

8.2. Site selection

Site selection should maximize the site specific advantages, and the disadvantages should be accounted for by the design and engineering of the waste management facility. The processes used in both the mine and mill operations will have a direct influence on the waste management requirements, performance, size and cost.

The site assessment for a tailings impoundment should include the drilling of a number of boreholes, down to bedrock, if required, in a grid pattern throughout the area, as well as the taking of undisturbed soil samples of the various subsurface soil layers. The horizontal and vertical permeabilities of the soils encountered should be determined by laboratory testing of undisturbed soil samples. In situ permeability measurements down cased and uncased boreholes should be performed during the drilling programme. This information will enable an estimate to be made of the rate of seepage from the tailings area. The material used in the construction of the embankment should be laboratory tested for horizontal and vertical permeability at various conditions of moisture.

The site selected should be amenable to effective decommissioning and to minimizing reliance on institutional control to ensure the integrity of the waste management facility in the long term. Preference should be given to sites which exhibit naturally occurring characteristics which will assist in ensuring the long term stability of the wastes.

Normally, for economic reasons the waste management facilities are sited close to the mine/mill facility. However, the operator should consider the other factors discussed in this section before deciding on the final location.
Evaluation of these characteristics will identify environmental constraints relevant to each proposed site, and allow the selection of a minimum number of sites which can then be evaluated in some detail, and from which the final site can be chosen and evaluated in a more detailed fashion.

The major characteristics which affect waste management practices are climate, meteorology, geography, geomorphology, demography and land use, geology, seismicity, geochemistry, mineralogy, hydrology and flooding, flora and fauna, and amenability to decommissioning. In the evaluation of a tailings impoundment facility, the concepts of both storage and disposal should be addressed.

8.2.1. Climate and meteorology

Precipitation and annual evaporation at a site virtually decide whether all the liquid wastes can be retained in the waste retention system, or whether liquid waste will have to be discharged to the environment through controlled releases. If the average annual evaporation exceeds the average annual precipitation and if seepage losses are estimated at zero or some other value, it is relatively simple to calculate the area of the waste retention system required to evaporate all the effluent. Consideration must then be given to the distribution of the rainfall, both throughout the year and from year to year, to ensure that adequate freeboard in the waste retention system is available at all times. For such systems it is essential that the catchment area draining to the waste retention system is not much greater than that of the system itself.

If rainfall is unevenly distributed, it may mean that rivers or streams will dry up during the dry season, so that effluents cannot be discharged to them. Another effect which has to be considered is the possible seasonal variation in the water table, which could affect the rate of seepage from the waste retention system and the rate of transport of contaminants through any aquifer which may be present.

The rate of rainfall is important since it determines the loss of material from waste rock piles, ore storage piles and the waste retention system as a result of sheet, rill or gully type erosion.

The magnitude and frequency of floods should also be considered in the siting and design of a waste retention system.

The daily and seasonal fluctuations in surface ground temperatures also influence waste management practices. Similarly, the inversion characteristics of the mine and mill sites are an important consideration. A knowledge of the frequency, duration, strength and break-up interval for atmospheric inversions is needed for the calculation of the concentration of airborne contaminants arising from mining and milling operations. If sulphuric acid is also manufactured at the mill, similar calculations need to be performed with respect to SO\textsubscript{2} damage to vegetation and possible acid mist damage and the exposure of the general population during inversion conditions.
Wind direction and speed should be considered, especially in arid conditions, to assess wind erosion of wastes and dust transport. Where suitable conditions can be demonstrated to exist, it may be possible to dispose of wastes using wind erosion if approved by the competent authority. Temperature inversions also have to be considered in assessing the effect of radon emanation from wastes.

8.2.2. Geography, geomorphology, demography and land use

These factors have a large influence on the waste management practices adopted at a particular site. For instance, the geomorphology of a site may not allow the siting of a waste retention system proximate to water bodies. The presence of adjacent farms, towns, or cities as well as the present and potential land use may impose additional constraints. The diet and recreational and working habits of the local inhabitants usually determine the characteristics of the critical group used for radiological calculations.

8.2.3. Geology and seismicity

The geology of the area influences selection of the site for a large embankment, as suitable foundations are essential for stability. Interactions between seepage and the foundation rock could, with time, increase the rate of seepage, an example being sulphide bearing waste material resting on a dolomite bed.

The seismicity of the area should be considered when siting and designing waste retention systems, since deformation and possible consequent liquefaction due to earthquake shocks can have serious structural consequences.

8.2.4. Geochemistry

Geochemical properties prevailing in the proposed sites should be considered to assess the final location and performance of the waste management facility. Chemical interactions of the wastes with the underlying strata of the site would influence the migration of the contaminants, with individual species being retained, retarded, or unaffected, depending on their specific chemical interactions.

8.2.5. Mineralogy

The choice of the uranium extraction process is largely determined by the effects of gangue minerals. These consequently have a major impact on waste management technology.

For example, milling of sandstone ores normally results in a larger proportion of slimes than in the case of conglomerates. Slimes present particular problems in an impoundment facility due, for example, to retention of pore liquid resulting in
slow drainage and consolidation. However, quartz pebble conglomerates are often associated with high pyrite content, which can result in acid generation in the tailings impoundment. Vein type deposits exhibit characteristics intermediate to quartz conglomerates and sandstones.

The mineralogy of soils and the subsurface of areas under consideration for mill sites and waste retention systems deserve greater attention than they have received in some cases. For example, an area with high limestone or dolomite content near the surface may prove unsatisfactory for a waste retention system if the wastes contain sulphides that can be expected to generate acid. Continuing acid percolation into the subsurface can dissolve carbonaceous rocks, opening channels for solution loss from the site, and also possibly affecting the stability of the waste retention system.

8.2.6. Hydrology and flooding

The hydrology of the site is of great importance as the wastes could contaminate either surface or groundwaters.

Knowledge of watershed areas, drainage systems, flow characteristics, storm events, flood plains, water balance, water quality, water table depth and magnitude, and proximity of springs and wells are all necessary to assess the amount of infiltrating water and its characteristics.

Infiltration into the mine workings and in some cases into the waste retention system influences the composition of mine drainage and waste seepages and can affect their management.

Where suitable hydrological conditions can be demonstrated to exist, it may be satisfactory to dispose of effluent by injecting it into a confined underground aquifer [26] containing non-potable water or to discharge it to lakes, rivers, streams or the sea using controlled releases [11]. However, such discharges must be approved by the competent authority.

8.2.7. Flora and fauna

The nature of aquatic and terrestrial habitats influences the degree of environmental impact that would result from waste management practices. Siltation can cause loss of fish breeding grounds and reduce egg hatchability. Discharge acidity affects plant nutrition and in severe cases leads to loss of bank vegetation and bank stability. Fish, macrobrachium sp. and zooplankton are very sensitive to heavy metal ions and the softer the water the more sensitive they are. Discharged tertiary amines reduce phytoplankton productivity, the effect being more marked if kerosene is also present.
Water quality also influences the bioaccumulation by aquatic organisms of radioactive and non-radioactive heavy metals. This, as well as the soil-pasture-stock transfer mechanism, should be taken into account in the assessment of the radiological impact.

8.3. Environmental impact assessment

In order to assess the impact that a proposed mine, mill and associated waste management facility would have on the environment, it is necessary to undertake a pre-operational data collection and analysis programme incorporating the factors in Section 8.2 of the Guide. The requirements for this programme may vary from country to country, but the final document produced constitutes an environmental impact assessment.

In addition to the data mentioned above, programme requirements may include the collection and analysis of parameters such as:

— the concentrations of the important radioactive and non-radioactive components of the area in air, water and soil, and in the flora and fauna of the area;
— the local gamma radiation levels.

It is important that a properly designed sampling and monitoring programme be established and implemented early. The purpose of the programme would be to provide data for site selection and modelling and later to calibrate and validate the models and thus provide a frame of reference for decommissioning.

8.4. Design considerations

Important considerations in the design of a waste management system are that there be minimum impact on the surrounding environment, minimum need to retrieve and relocate the wastes during or after decommissioning, and minimum reliance on continued surveillance and maintenance.

In designing an overall waste management system, it should be recognized that it is important to ensure that the performance of the system as a whole takes precedence over the design of the individual components. This may require the acceptance of less than optimal performance or conditions in one part of the system in order to achieve a concomitant improvement in some other part. For example, it may be necessary to increase the capacity or extent of the secondary effluent treatment if it is found that the areal extent of the primary effluent treatment system is a limiting factor. Continuous dialogue between a proponent/applicant and the competent authority regarding such system performance decisions is encouraged during the design phase.

Design submissions should be supported by the databases used in analyses, and by a discussion of the potential variability of all parameters. Where appropriate,
additional environmental field work and laboratory or pilot plant studies should be undertaken to verify designs. It is essential that design submissions characterize all liquid, solid and gaseous wastes resulting from the proposed operations.

In the design of the tailings impoundment, consideration also should be given to the following more specific features of the design, considering both operational and long term stability objectives, as appropriate:

(1) **Physical confinement of the tailings**, including:

- use of natural or excavated basins, where available;
- design of embankments or dams to assure functional integrity under all conditions over the proposed life of the facility;
- flood control and diversion works, including spillways, channels, dams and diversion channels for the control of contained liquids and other surface waters during storm events;
- placement of access and haul roads to avoid either short or long term impact on tailings impoundment;
- minimizing the exposed surface area of the tailings through such measures as staged disposal, progressive reclamation, or maintaining water, ice or snow covers where site conditions permit.

(2) **Seepage control**, including:

- provision of sound foundations;
- use of low permeability liners, giving preference to natural materials where available;
- provision of underdrainage, seepage collection and return systems where appropriate.

(3) **Tailings management systems**, including:

- slurry delivery and distribution systems, including pipelines, pumps and controls, designed to operate, with appropriate backup systems, under all anticipated conditions;
- water systems for control, recycle and return;
- auxiliary facilities.

(4) **Effluent treatment systems**, including:

- addition of chemicals;
- settling and treatment ponds;
- discharge structures;
- evaporation ponds;
- filtration.
(5) Stabilization and decommissioning, including:
- contouring of the surface to minimize slopes and associated erosive effects;
- provision of diversion systems where necessary;
- covering and capping to provide protection against erosion and inadvertent intrusion;
- revegetation, where applicable.

(6) Pre- and post-decommissioning monitoring requirements, including:
- on-site and off-site atmospheric monitoring;
- on-site and off-site surface and/or groundwater monitoring;
- provision for surveillance to identify any degradation, e.g., monuments and markers for use as reference points in aerial inspection and photography and on-site survey and inspection.

A more detailed discussion of each of the above six subsystems can be found in Refs [13, 27].

9. COLLECTION, STORAGE AND TREATMENT OF WASTES

This section considers the collection, storage and treatment of wastes arising from the mining and milling of uranium and thorium ores.

9.1. Mine wastes

9.1.1. Exploration wastes

9.1.1.1. Trench rock

Materials taken from exploration trenches should be segregated to the extent possible such that the trench may be filled in an orderly manner on closure. For example, any overburden should be separated, as should broken rock having the lowest and highest radioactive content. When trenching is completed, the trench should be filled, first with the rock containing the highest radioactive content, then by the least radioactive material, and finally by any overburden.

9.1.1.2. Drilling sludge

Drilling sludge or drilling mud may become contaminated with radionuclides. The use of drilling sludge should be minimized to the extent possible, as should the use of water, and the re-use of drilling materials should be maximized. All practical measures should be taken to ensure that water and sludge is contained, and not allowed to be freely dispersed into the local environment.
9.1.1.3. Core samples

Provision should be made for proper storage of core samples produced during the exploration phase. Upon completion of exploration then either with no further development of the site or during the decommissioning phase, the samples should be disposed of in an approved manner.

9.1.2. Operational wastes

9.1.2.1. Waste, barren and low grade rock

Mine waste rock requires management during the early development, operation and decommissioning of any uranium or thorium mine. This material originates from the removal of rock in a mine, be it open pit or underground, in providing means of access to the ore body. Before rejection as waste or barren rock, the material may be assessed as to its radioactive content by various means, such as radiometric sorting, washing or screening, to segregate any economic grade material, for example, low grade rock. There is currently no uniform method of waste classification and management of waste rock.

Frequently, waste rock characteristics are more variable than those of the ore body, since the material may originate in the surrounding or overlying rock with little, or different, mineralization or it may be part of the ore body itself.

Waste rock can be utilized in a number of ways but the mineralogy, radioactivity and chemical reactivity of the waste rock should be assessed before a decision is taken to use it for any of the following purposes:

— as a source of uranium which can be recovered by heap leaching;
— to refill the workings, especially in open pit mines;
— for construction of embankments on the mine site;
— for construction of structures to divert runoff and water course streams away from waste retention systems; and
— for construction of roads and similar projects on the mine site.

Different constraints exist for each possible utilization of waste rock. For example, its return to open pits may not be suitable if the open pit has been developed through aquifers or if the waste rock contains active sulphides.

If waste rock is subject to heap leaching to recover uranium, then the extracted heap becomes a waste. Care should be taken, when siting and constructing such heaps, to minimize their eventual impact on the environment and the public.

Because it isolates waste rock from the external environment, disposal in the mine may be preferable if the hydrogeological, engineering, radiological and economic aspects are favourable. Where there is no alternative to disposing of waste rock in piles constructed above ground, these should be located to minimize impact.
on the environment and to ensure mechanical stability. Such piles should be constructed according to sound engineering practices. Consideration must also be given at the planning stage to the requirements to be met when the mine is decommissioned. Guidance for the designing of waste rock piles is given in Ref. [28].

The effects of any seepage from waste rock piles must be assessed, and provision for collection and treatment of this seepage must be made if required. The treatment can be similar to that for mine drainage (see below).

The environmental impact that could result from waste rock and heap leaching piles depends markedly on the mineralogy of the rock, the climatic conditions of the area, the construction of the pile and the site where the pile is formed.

For example, if the pile is formed by road haulage of rock, it will be steep-sided, except for the approach road, and will exhibit a low runoff coefficient. Thus a large part of the incident precipitation will ultimately appear as groundwater or surface seepage. If the waste rock contains active pyritic material, this seepage will have a low pH, high total dissolved solids and, if the mineralogy is complex, high concentrations of some heavy metals (e.g. Cu, Zn, Co, Ni, As), as well as radionuclides.

9.1.2.2. Scrap material and equipment

Scrap resulting from drilling, excavating, loading, transport and other equipment may become contaminated to the extent that it should not be disposed of with the normal scrap.

Valuable equipment in this category may be decontaminated if required for use elsewhere, or wrapped or contained during transport to be re-used in some other operation, but normal scrap with little or no recovery value may best be disposed of as radioactive waste.

For this contaminated material potential disposal sites that may be approved by the competent authority are a selected part of the mine, the waste rock pile or the waste retention system. The main criterion to be met is to prevent public access to the material.

Where disposal is to the waste rock pile or the waste retention system, it should be done in such a manner that the waste is buried in a short time.

9.1.3. Liquid wastes

9.1.3.1. Mine drainage water

Mine drainage water consists mainly of surface water or groundwater which has entered the workings through subterranean channels or fissures, or rainwater which has fallen or drained into open pit operations. Other sources may be drill water, drainage from backfill operations, drinking and washing water.
The volume of mine drainage water should be reduced, to the fullest extent feasible, by:

- re-use of water in the mine for drilling and dust suppression, provided it does not result in significant increase in radon levels in the mine;
- use of containerized water or water coolers for drinking water supply;
- reduction of groundwater seepage by grouting or diversion of surface waters;
- transporting tailings fill underground at the highest practical solids content;
- avoiding the use of fresh water for transporting tailings fill underground; and
- treatment of water underground for re-use. This can range from comprehensive treatment to simple settling of solids in sumps.

As the above measures may only effect a small decrease in the volume of mine water, all practical and economic measures should be taken to ensure that the quality of the water pumped from the mine is such that it can be used in the mill or elsewhere, thus reducing both the overall demand for fresh water and the final net effluent volume.

The quality of mine water may be improved by the following procedures:

- the use of polyelectrolytes to reduce the release of fines from hydraulic backfill;
- segregation of oil bearing drainage from such places as maintenance bays;
- reducing the wastage or disposal of unused ammonia based blasting compounds; and
- minimization of hold-up and possible oxidation of broken sulphide material within the mine so as to decrease the opportunity for acid generation and metal dissolution.

Mine water can contact the ore body for substantial periods of time, and thus may contain dissolved uranium, thorium, radium, radon, thoron, other metals, ammonium nitrate and oils and be quite acidic or basic. In underground mines where it may contribute appreciably to radon levels in mine air, the water should be collected as soon as possible and pumped to the surface with minimum aeration. It is preferable to use this effluent as make-up water in the mill if this is feasible, as in this way the number of effluent streams is reduced and any uranium in the water can be recovered.

If more water is available than can be utilized in the mill, then it may be discharged to the waste retention system without treatment if the latter is working on the closed system and has the capacity to evaporate the additional volume. If the waste retention system cannot accept the excess drainage, then it may be possible in some cases to discharge it under controlled conditions to surface waters or a confined aquifer, after treatment if necessary. The specific treatment and disposal of a mine water waste stream is dependent on local conditions such as the mineralogy of the ore body, climate, topography and the existence of an operating mill. Treatment
may include separation of uranium, radium, and other heavy metals before release by utilizing such processes as sedimentation, precipitation, lime neutralization, ion exchange, precipitation with barium salts, and scrap iron cementation processes.

Seepage from waste rock piles, abandoned heap leaching piles and ore piles is similar to mine drainage water and the above discussion applies. Further information is contained in Ref. [13].

9.1.3.2. Surface water drainage

Control of surface water is essential to ensure and maintain the separation of uncontaminated surface water and contaminated surface flows. The two principal objectives involved are to minimize the amount of contaminated water at the facility and to keep uncontaminated water away from any possibility of becoming contaminated. These principles should be considered in the siting and design of a facility. For example, upstream watersheds controlled by each site should be no larger than necessary, and the sites selected for the facility, or part thereof, should be amenable to engineered diversion of any excess drainage around the particular system. However, the need for the diversion of natural water courses should be minimized through site selection.

Hydraulic works, such as diversion channels, ditches, conduits, culverts, pumps and lines, control structures, dams, embankments and berms, should be designed with the following in mind:

— where failure of the proposed works could result in significant harm to the environment, life or property, design flows should be based on the probable maximum flood;
— where the probable detriment or impact due to failure can be shown to be less than the above, the regional storm may be used as the design basis; and
— in either case provision should be made for a controlled failure mode, which allows for the excess water to be quickly released from the containment area (e.g. provision of a spillway).

Hydrological parameters should be based on measurements from the actual watersheds involved, although where sufficient data are lacking, reference areas and other analogues should be used.

The designs to control surface waters should promote both the short term and long term functional stability of control works, and provide for a minimization of impacts on other systems of the mining facility. Passive control systems should be considered as prime candidates as these will minimize reliance on active maintenance in both the short and long term.
9.1.4. **Airborne wastes**

Radon is released from open pits, in mine ventilation exhaust, ore dust, and at all stages of the milling process, but especially during the crushing, grinding and leaching stages. There is, at present, no practicable method for removing this gas from ventilation exhausts. Thus the manner and rate of release have to be monitored and adjusted to comply with authorized limits. Stopping by means of closed bulkheads or brattices of mined out or temporarily abandoned mine areas should be considered as a method of reducing radon emissions from underground mines. The presence of porous rock may render sealing devices ineffective. Emissions from open pits and ore dusts may be controlled by water blasts and wetting agents.

9.1.5. **In situ leaching wastes**

Extraction of uranium by in situ leaching techniques is generally carried out by drilling a pattern of injection and extraction wells and circulating leach liquor through the orebody. The uranium is extracted from the pregnant solution after the barren solution is chemically adjusted and recirculated through the leaching field.

Because the leach liquor may pick up materials other than uranium, a portion or all of the barren solution may have to be bled off or treated to remove impurities or suspended solids prior to reinjection. Thus, some liquid wastes, sludges and filter backwash may be produced as waste. In one operation [29], chemical wastes from the plant are treated by evaporation in reservoirs with a low permeability lining, which are sized so that evaporation balances inflow. When operations cease, the wastes should be disposed of in an acceptable manner.

Also, as typical leaching operations call for maintaining a higher rate of extraction than injection (to maximize recovery of uranium and prevent pollution of surrounding areas), a small portion of the barren solution is wasted on a continuing basis. The wasted fluid can be evaporated as above, discharged to surface waters after suitable treatment, or injected as below into an approved aquifer (preferably confined and deep).

Additional liquid wastes may be produced when the leaching field is decommissioned. If the competent authority requires the site be left in a chemical and hydrological condition similar to that before the extraction of the uranium, it may be necessary to use large quantities of water to elute the residual leaching solution. Disposal of this waste may not be possible without prior treatment.

The sources of air emissions in the processing of the leach liquor are limited to open tanks containing leaching solutions which may release radon, and dust from the yellowcake drier. The former is not a significant environmental hazard and the latter can be adequately controlled by an appropriate filter or scrubber.

Apart from the radium and other contaminants in the sludges mentioned above, there are no solid wastes, since the radium contaminated residual orebody remains underground.
9.2. Mill wastes

9.2.1. Solid wastes

9.2.1.1. Tailings

After the uranium is extracted from the ore, most of the remaining ore material becomes a mill waste or tailings, commonly a slurry of finely ground solids in waste solutions. The tailings slurry is pumped to a waste retention system where the solids settle out and accumulate. In a few locations the ore is processed without fine grinding, and the resultant tailings are transported in a nearly dry form to the waste disposal area. If this is the case, these tailings could be covered gradually while milling operation continues. This means that the area of uncovered tailings under operation is minimized, and that the final decommissioning is facilitated.

As the major portion (at least 97%) of the radium-226 input to the mill remains undissolved through the leaching process, the concentration of radium in the tailings is only slightly less than the concentration in the ore [26, 30]. If unprotected, the tailings release radioactive material to the air as radon gas and as airborne particulates and to waterways as radionuclides leached out by precipitation, surface runoff, and the waste solutions. Sufficient radioactivity is present in the tailings to create a weak field of gamma radiation in their immediate vicinity. Chemicals contained in the tailings, including various heavy metals, sulphates and sulphuric acid, may also be leached from the tailings into surface or subsurface waters.

Because it isolates the material from the external environment, backfilling of all or part of the tailings into worked-out portions of the mine would appear to offer considerable promise if the whole operation were to be planned on this basis. However, there are considerable difficulties of an economic and practical nature and a number of disadvantages. Firstly, the tailings consist of sand and slimes, and normally only the former are satisfactory as backfill for underground mines. Secondly, most of the radium and other decay products are contained in the slimes which, after separation of the sand, still have to be disposed of in waste retention systems. Thirdly, the structural and horticultural properties of desanded tailings are not as good as those of the original tailings; this leads to a greater likelihood of failure of the waste retention system and a more difficult revegetation problem.

Tailings backfilled into underground mines even with good engineering control may increase the contaminant level in mine drainage but should not provide additional problems. Those backfilled into open pit mines may cause contamination of groundwater or surface water with radionuclides, heavy metals and other environmental pollutants.

In certain instances the discharge of tailings into large water bodies may be proposed. Such proposals should only be made after detailed investigation of the site, and may require the inclusion of provisions to divert surface drainage. Where underground disposal of tailings is used, it is preferable in almost all circumstances to
practise deep water disposal. Density, temperature and the chemical content of the water in the discharge zone should be taken into account.

Tailings deposited in properly sited, engineered, and operated waste retention systems do not present a significant radiation hazard while the mill is operational. Even so, it is possible for an embankment to fail, a tailings pipe to burst and the resultant stream of tailings to wash away an embankment, or an unusual or unanticipated large rainstorm to overtop the embankment, releasing large quantities of tailings and contaminated effluent to the environment [31, 32]. Table I of Ref. [33] contains a listing identifying and characterizing several instances of embankment and other related failures at uranium processing sites in the United States of America during the period from 1959 to 1979.

After the facility has been decommissioned, control, surveillance and maintenance of these waste retention systems may present problems, some of which are:

(1) The slimes portion, aided by rainfall on and drainage into the waste retention system, may stay fluid for a very long period, exerting a continuous hydrostatic pressure on the embankment wall, which may, especially if weakened by erosion and seepage, eventually fail, leading to widespread release of tailings before the defect is observed and repaired.

(2) Revegetation of tailings impoundments may be difficult to initiate and even more difficult to sustain.

(3) The tailings are in a form which is attractive for civil construction purposes, and it is difficult to ensure that they are not unlawfully abstracted for this purpose. If they are used for construction of dwellings, then the inhabitants of the buildings are likely to be exposed to unacceptable levels of radon and radiation. Furthermore, no habitable structures should be built on the tailings.

(4) Tailings impounded by embankments built in valleys or natural drainage areas usually have a potential rainfall catchment area greater than those of free-standing impoundments. During operation of the mill, catchment from this additional area is normally diverted by means of dykes, bunds or ditches. When the site is decommissioned, it is possible that these structures will eventually fail, leading to excessive flows of rainwater onto the tailings with the possibility of erosion or possible failure of the embankment.

(5) Seepage from the tailings impoundments containing significant concentration of the radionuclides may eventually reach underground or surface waters that are used for irrigation or water supply purposes.

(6) Some uranium tailings present a different type of problem. Owing to the pyrite content of the ore, acid production occurs in the tailings.

The sulphides are oxidized by a complex series of reactions which may be generally described by the following equation:

$$4\text{FeS}_2 + 2\text{H}_2\text{O} + 15\text{O}_2 \rightarrow 2\text{Fe}_2(\text{SO}_4)_3 + 2\text{H}_2\text{SO}_4$$
The process of oxidation is both chemical and bacterial. The different forms of sulphide react differently but require water and oxygen. Light, temperature, acidity and bacteria will all influence the rate of reaction. Chemical oxidation is slow. More rapid oxidation by bacteria (Thiobacillus ferrooxidans) occurs only below pH 3.5-4.0 with optimum conditions between pH 1.5 and pH 3.5 [34].

The characteristics of a tailings impoundment will depend on such diverse factors as the capacity of the mill, type of ore processed, amount of waste produced, type of milling process, tailings density and settlement, topography of the area, amount of land available, net evaporation rate, permeability of the soil in the area, and the materials with which the impoundments are constructed. A number of countries have developed regulatory and design guides for these facilities [35-38].

As well as satisfying all the radiological safety, environmental and waste management aspects, the location selected for a waste impoundment system must also provide adequate safety for both workers and the surrounding population against a massive release of solids or liquids which may occur if the impoundment fails. This aspect should be given careful consideration.

A basic decision on whether the impoundment system will be used to contain all the liquid which is discharged with the tailings and not reclaimed for re-use, or whether some of it will be released to the environment, should be made before design is commenced. In the former case, the excess liquid will either evaporate or seep away. Under these conditions it is generally considered that seepage should be kept to a minimum, and a tailings impoundment facility should therefore be designed to have a stable, low permeability base and embankments. The impoundment also should be designed to incorporate a low permeability seepage barrier. In this manner all the solid and liquid residues are impounded, and the rate of release to the environment is controlled.

Where the evaporation rate or the area of the tailings impoundment system is not sufficient to evaporate all the liquid waste, the excess will have to be discharged to the environment. The decant solution can be discharged through a decant structure by gravity overflow, by pumps or by siphons. Siphons appear to be most satisfactory as they do not compromise the integrity of the embankment, they are accessible for inspection and maintenance, and they do not rely on power supplies.

To ensure compatibility, the procedures to be followed during tailings deposition should be established at the time the tailings impoundment system is designed. It is therefore essential that good co-ordination and co-operation is established between the designers and the future operators, and that the operating procedures are clearly described and made available to the operators. For this reason the operator should be fully aware of the operating procedures to be followed, and should take the responsibility of ensuring, by periodic inspection, that they are being followed.

Seepage, including that from engineered drains, can be intercepted and collected by suitable drains, ditches or wells. Where all wastes are intended to be
impounded, seepage should be returned to the tailings impoundment. When discharge of liquid waste is practised, the seepage can generally be treated and discharged with the decant liquor. For further details, see Section 9.2.2.

9.2.1.2. Heap leach piles

Heap leach piles are necessarily constructed so that the drainage from them can be collected and treated, generally in an existing mill, for the recovery of uranium. The leaching solution may be recirculated or, after the extraction of uranium, released with other liquid effluents. However, long after it is economic to recover the uranium, rainwater will seep through the pile. Such seepage, depending on the mineralogy of the material in the leached-out pile, may continue to extract small quantities of such elements as uranium, radium, and heavy metals.

It may be appropriate to dispose of a leached pile into an existing tailings impoundment or to provide appropriate cover material to control seepage. The final disposition of this pile should be approved by the competent authority.

9.2.1.3. Waste concentrates

Waste concentrates are formed as the result of a treatment process which is carried out to remove and concentrate hazardous material from a product or effluent stream. Although such concentrates are generally fluid sludges or wet filter cakes, they are considered as solid wastes because the hazardous materials are concentrated in the solid phase. A common waste which falls into this category is the sludge containing a mixed precipitate of Ba(Ra)SO₄ produced during the treatment of decant liquor.

The Ba(Ra)SO₄ sludge is usually allowed to settle from the treated decant liquid in large settling ponds, where it is normally allowed to remain. This does not appear to be a satisfactory method of long term storage of the hazardous waste concentrate, since it is not sufficiently isolated from the environment. It is considered that it should be returned to the tailings impoundment system in such a manner that it is more or less uniformly dispersed in the tailings. Alternative procedures which may be acceptable are solidification (either in situ or after collection) followed by burial at the site in the tailings, or in the mine.

An unusual and possibly unanticipated waste concentrate may be formed when sulphuric acid is generated from pyrite, recovered from uranium tailings, which contains some radium [39]. It has been found that the radium concentrates in scales formed in cyclones, pipelines and cooling, scrubbing and stripping towers. These scales may contain radium concentrations one or two orders of magnitude greater than in ore tailings. Disposal in the tailings may be approved by the competent authority.
9.2.1.4. Scrap material and equipment

Solid wastes from uranium and thorium milling operations may require handling as radioactive wastes if they are significantly contaminated with radionuclides. The wastes may include scrapped ventilation ducting, ion exchange columns, clogged filters, filter cloths and scrapped equipment from the uranium and thorium recovery, drying and packing areas. It is normal practice to consign this material to the tailings impoundment or to a special disposal site. Scrap containing large voids may not be placed in the impoundment, as this should lead to uneven settlement after rehabilitation.

9.2.2. Liquid wastes

9.2.2.1. Barren solution

In the alkaline leaching process, the barren liquor is recovered and re-used, and does not become a waste stream. The leached, washed tailings are transported to the tailings impoundment system in a water slurry. The water slurry is slightly alkaline, may be contaminated with radioactive nuclides and chemicals, and may need treatment before disposal.

In the acid leaching process, however, the solution that is normally used to transport the tailings may contain greater concentrations of contaminants. These could include sulphuric acid, heavy metals, nitrates, sulphates, organic solvents and amines (both from solvent extraction), chlorides and radionuclides [40, 41].

The most effective method for minimizing contamination of the environment by effluents from uranium milling operations is to avoid, or limit as far as possible, the discharge of effluents. In some instances this may be possible through complete recycle of the decant solution to the milling process if the metallurgy is not detrimentally affected. The amount of make-up water required should be reduced by optimizing water usage and practising water reclamation where possible. A detailed water balance should be made and periodically reviewed so as to ensure the optimum use of water throughout the operation. The mill process effluent is the waste component most likely to influence the treatability of waste streams and to affect the degree to which they can be recycled to the mill. Processes and reagents used in the mill should therefore be selected so as to reduce as far as possible any adverse effects on treatability and recycle capability. All working areas which may be sources of contaminated waste streams should be consolidated to the greatest degree feasible. For example, from the standpoint of drainage control, it is usually preferable to locate the mill, mine head, maintenance shops and materials handling facilities in one controlled area. On the other hand the relative advantage of segregating waste streams for treatment should also be assessed.
Where climatic conditions are favourable, the discharge of effluents may be avoided by evaporation of excess water from the tailings impoundment system. In this case it is usually unnecessary to treat the solution unless neutralization of the waste stream before discharge from the mill is required to suppress acid production in the tailings. Release of all or part of the treated or untreated effluent is generally regarded as less satisfactory but where the environment can assimilate the contaminants without any undue detriment, this method may be acceptable. Guidance on the safe disposal of radioactive waste into rivers, lakes and estuaries is given in Refs [11, 42, 43].

The main process for the treatment of acidic mill effluents is neutralization with lime or a combination of limestone and lime [44]. During this step the following purification processes occur:

— $\text{H}_2\text{SO}_4$ is neutralized;
— some sulphate is precipitated;
— heavy metals are precipitated;
— thorium-230, thorium-232, and lead-210 are precipitated or adsorbed;
— radium-226 is removed to a large degree and it appears possible to reduce its presence to 3 to 7 Bq/L or perhaps lower, by neutralization to pH 8; and
— amine is removed by adsorption on precipitated solids.

Although barium treatment to precipitate radium is usually carried out on clarified solutions, it has been shown [45] that, after neutralization to pH 8 to 9, the addition of $\text{BaCl}_2$ solution to liquor decanted from the mill disposal tank, followed by the addition of an aqueous solution of a sodium salt of a long chain fatty acid such as oleic, palmitic or stearic at a rate of 10 mg/L of effluent, leads to a flocculation of the sulphate by mixed oleates of calcium, barium and radium. Under these conditions, the rate of settling is enhanced. In addition, the precipitate formed is much less soluble than for the sulphates alone. If this treated liquor is then released with the tailings the radioactive particles are dispersed throughout the solid tailings, and this leads to a large reduction in specific activity.

Starting with effluents containing between 3 and 30 Bq/L of radium, the addition of barium chloride at 10 mg/L and of sodium oleate at 10 mg/L reduces the radium level to 0.1 to 0.2 Bq/L, a value which may be compared with levels of 0.05–1 Bq/L which occur naturally in some rivers.

9.2.2.2. Decant solution

Where it is intended to routinely discharge the decant solution in the tailings impoundment it may be helpful to neutralize the barren process solution before it enters the impoundment system. Even so, the decant solution can still contain from 3 to 30 Bq/L radium-226, sulphates and other contaminants.
The radium-226 contaminant, which should be reduced before discharge, can be coprecipitated with BaSO$_4$ by addition of BaCl$_2$ to the clarified liquor in the presence of excess sulphates at pH 8–9 and separated. It is imperative that the decant solution be free of tailings solids since the presence of such solids leads to less effective radium removal through the apparent replacement of radium in the solids by barium. BaCl$_2$ treatment when followed by adequate clarification may result in effluents containing as low as 0.1 Bq/L of radium-226.

The precipitate will normally remain insoluble and will not present an immediate hazard. However, if the nature of the liquid flowing over the precipitate changes either as a result of process changes or because the operation has ceased, resolubilization or resuspension of the precipitate may occur.

Depending on the extent of the mining operations this material will in some cases accumulate at a considerable rate and may have to be removed from the settling area and be relocated to the tailings impoundment or other acceptable area.

When operations cease, the material may be subjected to contact with rain or surface water of low sulphate content which may cause redissolution. It is important therefore to take this into consideration during decommissioning.

In formulating plans for treatment methods, the impact of the chemicals used, such as barium, on the environment may require assessment.

9.2.2.3. Tailings seepage

Seepage changes in character with time as the tailings impoundment fills up, and may present quite different problems at different stages. Initially the seepage corresponds quite closely in composition with the decant solution and contains appreciable quantities of radium, so seepage should be minimized to reduce the discharge of radium. As the embankment rises, the pond usually retreats from it and the seepage may consist more of rain water which has filtered through the tailings, and less of decant solution. Thus the radium level may drop and there may also be marked changes in pH, sulphate and metallic ions. These changes may continue long after operations cease.

Of particular concern is the production of acid in aged sulphide bearing tailings. This can lead to a higher acidic seepage which may contain high levels of such constituents as heavy metals, manganese and sulphate, although the radium content may be quite low.

When there is no discharge of effluent from the system, it is normal practice to collect the seepage and pump it back during the operational phase. Alternatively, the seepage can be collected in a basin downstream of the impoundment where it can then evaporate leaving a salt deposit. When operations cease, the salt should be retrieved and disposed of in an acceptable manner.

In situations where there is discharge of effluent from the system, seepages are normally collected and treated along with the effluent. When operations cease, the
tailings in the impoundment system are consolidated by drying out or drainage, eventually reducing the quantity of seepage. Contouring and stabilization of the tailings to promote runoff can reduce seepages further.

9.2.2.4. Thorium milling effluent

The liquid effluents from thorium milling consist of plant and floor washings, filtrate and filter cake washings. They may contain some particulate material and salts, acids, thorium, uranium and rare earths in solution. These wastes can be treated through a set of settling tanks before release to a river having a high flow rate. To further reduce the radionuclides in the liquid effluents, additional settling and filtration facilities and a radium removal step can be used. Assessment of the environmental impact associated with the disposal of monazite processing waste is complicated by the varying degree of separation achieved for thorium and daughter products, the concentration of the various daughter products, and the buildup of activity after processing.

9.2.2.5. Plant washings

The wash water resulting from cleaning equipment and floors in the mill and other plant buildings is normally directed to collection sumps. Solids contained in the wash water, particularly from floors, will settle in the sumps. Sump water can be recycled in the mill, used for slurrying tailings, or pumped to the tailings area.

9.2.2.6. Laboratory wastes

These are generally samples, both solid and liquids, waste solutions, reagents and organic materials. All laboratory wastes should be contained in suitable containers, and disposed of in appropriate places such as the mill circuit, tailings or special waste sites.

9.2.2.7. Laundry water

Laundry water will contain particulates and soluble materials washed out of clothing. This water should not be recycled, but should be used as make-up water to the mill or be directed to the waste impoundment facility.

9.2.3. Airborne wastes

Dry ore dusts are normally generated during crushing and dry screening operations. They are removed by dust extraction units incorporating features such as hoods, ducts, fans, cyclones and wet scrubbers to capture particles and return them
to the process stream. Roasting of ores requires dust recovery equipment incorporating features such as dry cyclones, wet scrubbers and possibly electrostatic precipitators. Dust removal equipment should also be provided to trap dusts resulting from dry reagent handling operations. Two such reagents are pyrolusite, employed as an oxidizing agent during the sulphuric acid leach, and unslaked lime, which is used for pH control and effluent treatment.

Fumes arising from the use of nitric, sulphuric and hydrochloric acids as well as fumes from high temperature leaching operations are normally exhausted to the atmosphere by employing fume extraction hoods and fans. When ores release gases such as arsine, stibine, hydrogen sulphide and sulphur dioxide during acid leaching, the fumes may in addition require treatment in wet scrubbers before release to the atmosphere. Mists containing ore particles generated during rotary vacuum filter-cake blow-off cycles are also exhausted to atmosphere.

Separation of diuranate (yellowcake) from filtrates by centrifugation or filtration should be carried out under adequate exhaust ventilation. Air containing particles of yellowcake may be scrubbed with dilute acid or water and filtered for recovery of the uranium. Product drying and packing operations require similar dust removal and recovery equipment.

Windborne particulate material originating from the surface of the tailings impoundment system may also be of some significance. This release presents a potential health hazard which requires evaluation.

The radiation dose to the public can be decreased by: controlling the emission to the extent practicable; siting tailings impoundments systems as far as possible from established residential areas; and restricting the development of new residential areas close to operating or non-operating tailings areas.

10. OPERATION OF WASTE MANAGEMENT FACILITIES

The Code requires the waste management facility to be constructed to a plan approved by the competent authority and operated in accordance with the terms and conditions of the authorization or licence given by the competent authority.

While some of the requirements for the operation of a waste management facility have been addressed in previous sections, the more specific information which may be required of the operator by the competent authority before the facility is operated is contained in what follows:

— a description of the design, construction and operation of the facility;
— detailed descriptions, with drawings, of the facility, including: all structures and equipment designed to retain and control the tailings; the quality and quantity of all effluents and emissions from the facility; and structures and equipment designed to divert or control the flow of uncontaminated surface waters;
— the expected total volume and flow rates of all liquids handled by the facility, and points of discharge;
— the expected chemical, physical and radiological characteristics of all effluents and emissions discharged from the facility;
— the anticipated flow networks for liquid and solid waste streams within the facility, including the flows of any fresh water;
— detailed plans for monitoring the quality and quantity of effluents and emissions discharged from the facility, including:
  • sampling points, methods, frequency and parameters, methods of analysis, and equipment;
  • contingency plans in the event of abnormal results;
— an assessment of the impact of accidental or unscheduled releases from the facility, and proposed contingency and mitigative measures to be adopted;
— an operational procedure manual for the operation of the facility, including operating procedures for all components; and
— conceptual decommissioning plans.

Sampling techniques and analysis methods should be documented, particularly if analyses are carried out by the owner/operator/manager.

The operation of the waste management facility should be in accordance with the information and procedures outlined above. The operator should develop and implement a programme of regular inspection, quality assurance, maintenance and equipment testing, and incorporate it into the operations procedure manual.

Quality assurance as required by the Code refers to actions which provide a means for controlling and measuring the characteristics of an item, process or facility in accordance with requirements of the competent authority. Quality assurance involves planned and systematic actions necessary to provide adequate confidence that an item or facility will perform satisfactorily in service.

The plan for monitoring releases should describe the parameters to be monitored, the point of sampling and the sampling frequency, data logging and reporting procedures. Interpretation and analysis of data will be an important aspect of the plan and the reporting documentation.

Contingency plans should address accidental and unscheduled releases from the facility, and provide a response guide to such releases. The plans should include a list of key personnel and indicate the nature of the work done in various sections of the facility. The reporting requirements of the owner/operator/manager and of the competent authority should also be included. Such plans should be readily implementable.

During operation particular attention should be given to the handling and control of the liquids in the treatment, storage and impoundment facilities and to the potential impact of surface water external to the facilities. Specifically:

— Primary effluent treatment should provide for control of the general physical and chemical characteristics of discharged tailings; keeping standing water remote from embankments; control of short-circuiting within the tailings pond;
control of the physical and chemical quality of primary treatment discharges. Programmes for monitoring the primary effluent treatment should provide for: the volume and amount of wastes discharged into the primary treatment system; the liquid level in the tailings pond; and the quantity and quality of discharges from the primary treatment system.

— Secondary effluent treatment should provide for control of the general physical and chemical characteristics of inflows and outflows; regular inspection of treatment ponds, with particular note of the physical aspects such as the functioning of baffles, flows, ice or flood conditions, and the overall integrity of the systems, including pump and filter operation, and other aspects related to the mechanical integrity of the system; operation of the waste water treatment plant and the maintenance of an adequate supply of reagents. Effluent from the secondary treatment facility should be monitored to ensure that it meets the required standards and objectives, and the monitoring results recorded, and reported as required. Such monitoring programmes should be designed to provide information on the quality and quantity of influent; final effluent; treatment efficiency; reagent addition rates; and the quality and quantity of any seepage.

— Regular inspection and monitoring of surface water should ensure that any degradation of the treatment, storage and impoundment facilities is detected and repaired before a major loss of containment or other event occurs.

11. DECOMMISSIONING OF MINES, MILLS AND WASTE MANAGEMENT FACILITIES

As indicated in the Code, careful attention should be given to the decommissioning of the mine, mill and waste management facilities at the end of their useful life in order to put these facilities into a safe condition and to assure the stability of the mill tailings and any other wastes to be left at the site.

In the planning and engineering of the final decommissioned facility, consideration must be given to the degree to which reliance is to be placed in the long term in maintaining site integrity through passive design features as opposed to continuing active surveillance and maintenance.

In general, the passive design approach will be characterized by higher initial costs. Emphasis would be given to the selection of geomorphologically stable sites, and the passive design approach would employ design features such as gentle slopes, substantial covers of earth, rock armouring, and, where appropriate, liners for groundwater protection and measures to control the encroachment of surface water. Another basically passive feature to aid in assuring that the above design features will not be disturbed by deliberate or inadvertent intrusion is to provide for governmental ownership of the site in perpetuity.
In contrast, primary reliance may be placed upon long term institutional control, with continuing active surveillance and maintenance of the site. In this approach the initial cost would be minimized and higher continuing costs would be anticipated. The passive features of the design would be minimized, resulting, generally, in thinner covers, little or no armouring, less effective protection against erosion, etc. However, in this approach the integrity of the site would be maintained through continuing active surveillance, followed by maintenance and repair when required.

It should be recognized that these approaches are not mutually exclusive and that the final design will represent a judgement as to the optimum balance between the two, taking into account site specific features, national objectives and priorities, responsibilities of the parties involved, etc. Thus, in the passive design approach, some limited surveillance and maintenance would be anticipated, but this would serve primarily as a backup. Similarly, with primary reliance on continuing institutional control, some protective features would be provided, but these would serve primarily to provide the basic control of the wastes required, with limited allowance for long term deterioration.

The following sections provide more specific guidance on the decommissioning of the mine, mill and waste management facilities.

11.1. Mine

It is expected that the site will, after decommissioning, be subject to a covenant or other arrangement restricting its further use. The area for which restrictions are necessary should be minimized to the extent practicable through the use of good practices during the operational life of the complete facility.

11.1.1. Underground mines

All openings to the surface should be sealed in an approved manner. Additionally, actions may be required by the competent authority in individual situations to prevent the pollution of aquifers and surface waters.

11.1.2. Open pit mines

The slopes of the open pit mine should be stabilized if required and posted in an approved manner. Additionally, actions may be required by the competent authority in individual situations to prevent the pollution of aquifers and surface waters.
11.1.3. In situ leaching

It may be required in the case of in situ leach mining to restore the water in the mine to acceptable standards during decommissioning. This may be accomplished by using water to elute the mine until these standards are achieved. A decommissioning proposal should be submitted for approval to the competent authority.

11.2. Mill

The decommissioning of mill sites may require the removal of contaminated ground, floors and building foundations. These wastes may be deposited in the tailings impoundment or buried under a cover of earth or waste rock. The decommissioning of heap leach piles may require their removal and placement in the tailings impoundment, or their covering with suitable materials such as waste rock or other locally available materials.

11.3. Waste management facilities

Before stabilization can begin, the final form of the tailings impoundment must be decided. Typical questions which should be answered are:

— Will the normally present central depression of the tailings surface be retained?
— If so, will an accompanying pond or lake be retained and how will the water level be controlled?
— If not, how will the depression be filled, and will the final surface be flat or contoured to a slightly convex or concave shape?
— Will the embankment side slopes be flattened, and if so, how will this be achieved?

No firm guidance can be given on these points, as the best answer in each case is dependent on the actual conditions which exist at the site. All decisions, however, should be taken with the object of maximizing the stability of the system, which is of paramount concern in providing safety in all circumstances. Some procedures which may be applicable in some cases are to cover the wastes with barren crushed rock (possibly waste rock from the mine) to a sufficient depth, or to stabilize the surface using vegetation, chemical admixtures [46], clay, cement or bitumen. It may be possible to relocate waste rock back into the open pit. If this is not possible, and if the waste rock contains sulphide gangue minerals and uranium minerals, it may be necessary to reshape, contour and cover the pile with a low permeability soil/rock cover to reduce water infiltration. The cover would reduce the formation of acidic seepage which could carry base metals and radionuclides in solution into surface and groundwater.
The decommissioning of other waste management facilities, e.g. settling ponds, is normally accomplished by removal of contaminated materials and their placement into the impoundment systems.

11.4. Decontamination

Permissible levels for surface contamination of skin, clothing and work surfaces and the decontamination of equipment and buildings have been extensively reported [47-51]. This is not the case with the decontamination of land. Furthermore, there are no internationally agreed permissible levels for land contamination. Acceptable land contamination levels may be influenced by the nature of the contaminating radionuclides, the properties of the land surface, degree of occupancy and use, and the local climate.

It is suggested that levels which represent some low multiple of the natural background in the environs should provide adequate safety and be readily attainable. In general, the ‘as low as reasonably achievable’ concept should apply.

Areas which have been contaminated by tailings, waste rock or ore piles can best be decontaminated by removal of surface layers of soil or rock by scrapers, excavators, bulldozers, rippers, etc., followed by the selective removal of any remaining more deeply buried material that may be detected by survey instruments. The decontamination procedures should be continued until the residual contamination of the surface is reduced to an acceptable level. The contaminated material so removed may be treated in the mill for recovery of contained uranium and thorium. Alternatively, as approved by the competent authority, this material may be disposed of directly to waste rock piles, the tailings impoundment or the mine.

11.5. Intrusion and misuse

Human intrusion into the decommissioned tailings impoundment is to be discouraged in order to prevent long term occupancy, erection of structures, possible disruption of the integrity of protective features, removal of tailings, etc. This may be prevented by some combination of means such as the following: governmental ownership, placing of information or restrictions on title deeds or land records, substantial tailings covers, massive stone, concrete or metal markers, fences, and conventional signs.

The methods employed will be determined in large measure by the basic approach adopted in the decommissioning of the facility, i.e. the passive design approach or the active surveillance and maintenance approach (see Section 11). In general, the former approach will provide basic protection through substantial physical covers while the latter may rely more heavily on fences and signs, which will require periodic maintenance. The protective features to be employed should be proposed for approval by the competent authority. Irrespective of the basic approach
adopted, it is recommended that strong consideration be given to the benefits of permanent governmental ownership and the use of a permanent massive marker or markers to identify the site.

**11.6. Decommissioning in Member States**

Early experience with the decommissioning of the mine, mill and waste management facilities was mixed. In many cases such facilities were abandoned with little attention to decommissioning requirements, while for other facilities more responsible approaches were followed. More recently, however, requirements for decommissioning and, in some cases, provisions for financial guarantees have been established by the competent authorities.

Following is a brief summary of the experience and existing situation in Member States:

**United States of America**

The United States has issued "Environmental Standards for Uranium and Thorium Mill Tailings at Licensed Commercial Processing Sites" [52], which include provisions for decommissioning. The United States has also issued Standards for Remedial Actions at Inactive Uranium Processing Sites [53], which cover the cleanup and stabilization of 24 mill sites abandoned in the 1950s and 1960s, and for the cleanup of off-site properties in the vicinity of these sites. Following is a summary of the basic numerical standards established by these documents. This summary is an amalgamation of the standards for the licensed sites and the inactive sites. For specifics as to applicability, reference should be made to [51] and [53]. A discussion of the rationale upon which the standards are based is contained in the Environmental Impact Statements accompanying these issuances [54, 55].

1. **Cleanup of land**
   - Maximum concentration of radium-226: average over any 100 m² area
     - Top 15 cm (average) 5 pCi/g
     - Below 15 cm (average over 15 cm layers) 15 pCi/g

2. **Decontamination of habitable structures**
   - Maximum radon daughter concentration, including background: 0.02 working levels to the extent reasonably achievable, but not to exceed 0.03 working levels.
   - Maximum gamma, above background: 20 μR/h
(3) Stabilized tailings/waste impoundment

The final disposal facility shall be designed to meet the following criteria for a period of 1000 years to the extent reasonably achievable, and in any case for at least 200 years:

— Maximum radon release rate: 20 pCi/m² per second
— Groundwater to be protected to background or safe drinking water levels in accordance with the rules of the Solid Waste Disposal Act [56].

In accordance with the above standards, the US Department of Energy has under way a programme for the cleanup and stabilization of the 24 inactive processing sites mentioned above and for the cleanup of an estimated 4500 contaminated properties in the vicinity of these sites. This programme is scheduled to be completed by the early 1990s. Under the terms of the existing legislative framework, the licensed, commercial processing sites will be decommissioned by the site owner/operator at the end of their useful lives. A number of these sites have recently been shut down. Decommissioning activities are under way at some sites and plans are being formulated for others. The 'competent authority' responsible for review and approval of decommissioning plans and activities is either the US Nuclear Regulatory Commission or the equivalent body of the State within which the site is located.

Canada

In Canada several uranium mine and mill sites have recently closed down and decommissioning activities are being pursued. The approach used in decommissioning one of these mine/mill facilities is presented in a paper by Ashbrook [57]. This reference contains details of decontamination procedures and goals for controlling releases to the environment. Canada’s competent authority, the Atomic Energy Control Board, is also developing the necessary administrative/regulatory mechanisms to deal with this stage of the fuel cycle [58, 59].

Australia

In Australia decommissioning activities are managed in accordance with a Code of Practice on the Management of Radioactive Wastes from the Mining and Milling of Radioactive Ores published in 1982 [60]. A guideline to the Code is about to be published elaborating on the measures to be taken in decommissioning and rehabilitating uranium mine and mill sites. A guideline on radioactive waste management for the mineral sands industry is currently being prepared [38]. Abandoned sites, where uranium mining and milling operations took place in the 1950s and 1960s, are being progressively rehabilitated [61–63].
France

In France a joint procedure of Health and Industry Ministries is applied on a case by case basis. Cleanup levels are set and compliance with them is checked through inspections. An ‘arrêté’ issued by the head of the ‘Département’ gives precisely the measures to be taken in order to assure protection of the public and the environment. This ‘arrêté’ includes:

— definition of and responsibilities in the monitoring and sampling programmes;
— restrictions to access, digging, use of water, material, flora, hunting and fishing, and transfer of ownership.

Representations can be made to the head of the ‘Département’, who, after being advised by the above Ministries, can authorize modifications to the conditions of the ‘arrêté’.

12. MONITORING, SURVEILLANCE AND MAINTENANCE

The goals of pre-operational, operational and post-operational monitoring and surveillance as presented in the Code are:

— to determine whether there is compliance with regulations and procedures of the competent authority;
— to provide data from which individual and collective dose rates resulting from the facility may be assessed;
— to check the effectiveness of engineering designs and technical solutions, and the models employed for the design;
— to indicate whether or not discharge authorizations should be redefined;
— to trigger special inspections if needed;
— to identify unexpected environmental contamination and transfer routes and pathways;
— to check the physical condition and integrity of the waste management facilities so that repairs can be effected if needed; and
— to collect data for information and advice to the public if necessary.

The following sections provide guidance on the monitoring of surface and groundwater, the atmosphere, liquid effluents, airborne emissions, other monitoring requirements and the surveillance and maintenance programmes. Monitoring and surveillance are discussed also in Section 10 of the Guide.
12.1. Monitoring the aqueous environment

A comprehensive and well-designed programme for monitoring the aqueous environment is required during the pre-operational, operational and post-operational phases of a uranium or thorium mine/mill facility.

The basic method used in these programmes is to monitor groundwater through boreholes and wells, and to collect samples from surface water bodies. It may be possible sometimes to monitor groundwater that reaches the surface through springs or natural depressions.

In regions where more than one hydrogeologic unit may be affected by releases of radioactive material, the monitoring wells are planned in such a way that each well or borehole yields samples from only one hydrogeologic unit. Areal and vertical spacing of monitoring wells should be such that all the hydrogeologic units which may be contaminated are monitored and taken into account. Therefore, the monitoring design will be based upon the local groundwater flow system and should be derived from any available flow and transport analyses made, for example, on models. Homogeneous formations generally require fewer wells than do heterogeneous formations. If the hydrogeologic unit to be monitored is of considerable thickness, samples should be obtained from several different depths. In general, most of the monitoring wells should be down-gradient of the facilities, but not necessarily in the same lateral direction for all hydrogeologic units that are monitored.

The programme of monitoring the hydrogeologic system in the region should be initiated one or two years before the start of construction of the facility and should be designed to take into account the variations relevant to the site (e.g. seasonal changes). Statistically reliable background data on the groundwater system normally should be available by the time the facility goes into operation. Such data collected in the pre-construction and pre-operational periods can serve as a basis for comparison with data obtained during the operational phase of the facility, and with that resulting from the monitoring programme established to verify the effectiveness of decommissioning activities.

12.2. Monitoring liquid releases

The competent authority should set or approve locations for release, sampling schedules and limits for both radioactive and non-radioactive components in effluents from the waste management facilities to the environment. In addition, as required, there should be monitoring requirements placed on releases such as seepages or runoffs from waste rock and ore stockpiles, mill yards and the dewatering of mines. These releases may require treatment or, if below limits acceptable to the competent authority, they may be discharged directly to the environment.

During extended shutdowns, and post-operational and decommissioning activities, monitoring requirements for liquid and airborne releases to the environment...
should be set or approved by the competent authority. Following decommissioning, compliance, for some predetermined period of time, with the limits established should indicate successful decommissioning and lead to the release of the owner/operator/manager from further responsibility for the decommissioned facility.

12.3. Monitoring the atmospheric environment

A comprehensive atmospheric environment monitoring programme should be established during the three phases of a facility’s life. Pre-operational sampling of the atmosphere for radioactive components such as radon, its decay products, uranium and thorium and their long lived decay products, and non-radioactive contaminants such as oxides of sulphur and nitrogen acid mists and particulates should be required for environmental baseline data for use in the preparation of an impact statement. Continued sampling of the atmosphere at locations designated or approved by the competent authority should be required to demonstrate compliance, to verify parameters used in the design and to verify the effectiveness of controlling airborne emissions both during operation and decommissioning.

12.4. Monitoring airborne releases

Emissions of particular concern at the site of a typical mine, mill and associated waste management facility that produces its own H₂SO₄ and/or uses diesel oil for generation of heat, steam and power, are oxides of sulphur, nitrogen and particulates. In addition, during operation all conventional facilities emit radon, its daughter products, and ore and product dusts. During decommissioning there may be emissions of radon, its daughter products and radioactive particulates if the tailings impoundment is not well covered. Programmes should be set up to monitor these emissions to ensure that they are within the limits set or approved by the competent authority.

12.5. Other monitoring requirements

It has been found that monitoring of other environmental components, such as flora and fauna, dairy products and other foodstuffs, has been necessary in some situations. The need and extent of such monitoring should be as set or approved by the competent authority.

12.6. Operational and post-operational surveillance and maintenance

Maintenance should be provided, as needed, during the operation of the facilities to assure their continued efficiency, safety and environmental compatibility.
From an environmental standpoint the need for such maintenance is most likely to arise from the findings of the monitoring and surveillance programmes, particularly as concerns groundwater contamination, where the consequences of leakage or abnormal seepage from impoundments may not be directly observable. Maintenance during the operating phase may lead to some modification of existing processes to permit temporary isolation and repair of a malfunctioning component or system. It is anticipated that for properly designed and constructed waste disposal sites, the maintenance required will be minimal and will consist of minor repairs. However, more extensive maintenance may be required in unusual circumstances such as major flooding or earthquake damage.

Physical inspection of the site may include direct observation by competent individuals walking the site and additional techniques, such as systematic on-site photography to enable comparison with previous conditions, aerial observation and topography, and measurement and recording of the vertical or lateral displacement of bench marks installed during decommissioning. In walking the site, the inspection team would look particularly for signs of erosion, localized subsidence, seepage, changes in patterns of vegetation, evidence of flooding or flood damage, changes in on-site or nearby streams, etc.

Following decommissioning, surveillance and maintenance of the waste disposal area should be continued under terms prescribed or approved by the competent authority, and may include many of the requirements applicable to the operational phase. These terms should specify the minimum frequency of site inspections and the duration of the initial period during which surveillance and maintenance (if needed) are to be conducted. Surveillance inspections following decommissioning may include direct observation of the physical condition of the site and the sampling of air and groundwater.
This publication is no longer valid
Please see http://www.ns-iaea.org/standards/
REFERENCES


[54] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Final Environmental Impact Statement for Standards for the Control of By-Product Materials from Uranium Ore Processing (40 CFR Part 192); EPA 520/1-83-008-1, USEPA, Washington, DC (October 1982), Vols I and II.


[58] ATOMIC ENERGY CONTROL BOARD, CANADA, Regulations Respecting Uranium and Thorium Mining (under preparation).


LIST OF PARTICIPANTS

CONSULTANTS MEETING
Vienna, Austria
11 to 15 April 1983

Cook, J.E.
Regulatory Bureau,
Australian Atomic Energy Commission (AAEC),
P.O. Box 153, Rosebery, NSW 2018, Australia

Farges, L.
Centre d’études nucléaires de Fontenay-aux-Roses,
B.P. No. 6, F-92260 Fontenay-aux-Roses, France

ADVISORY GROUP MEETING
Vienna, Austria
3 to 7 October 1983

Ashbrook, A.W.
Eldorado Nuclear Limited,
400-255 Albert Street, Ottawa, Ontario, Canada

Boulden, R.
(Chairman)
Atomic Energy Control Board,
Martel Building, 270 Albert Street, P.O. Box 1046,
Ottawa, Ontario K1P 5S9, Canada

Chander, M.
Waste Management Division,
Bhabha Atomic Research Centre,
Trombay, Bombay 400 085, India

Cook, J.E.
(Consultant)
Regulatory Bureau,
Australian Atomic Energy Commission (AAEC),
P.O. Box 153, Rosebery, NSW 2018, Australia

Culver, K.B.
Rio Algom Limited,
P.O. Box 1500, Elliot Lake, Ontario P5A 2K1, Canada

Farges, L.
(Consultant)
Centre d’études nucléaires de Fontenay-aux-Roses,
B.P. No. 6, F-92260 Fontenay-aux-Roses, France
Haw, V.  
Nollman, C.  
Snihs, J.O.  
Thomas, K.T.  
Tison, J.L.  
Groelsema, D.H.  
Eldorado Nuclear Limited,  
Waste Management Operation Section,  
Regulatory Bureau,  
Centre d'études nucléaires de Fontenay-aux-Roses,  
Division of Uranium Mill Tailings Projects (NF-22),  
CANMET National Uranium Tailings Research Programme,  
National Commission of Atomic Energy,  
LKAB International AB,  
National Radiation Protection Institute,  
International Atomic Energy Agency,  
Cogéma,  
Eldorado Nuclear Limited,  
Waste Management Operation Section,  
Regulatory Bureau,  
Centre d'études nucléaires de Fontenay-aux-Roses,  
Washington, DC 20545, United States of America  
580 Booth Street, Ottawa, Ontario K1A 0E4, Canada  
8250 Avenida del Libertador,  
Box 5164, S-102 44 Stockholm, Sweden  
Box 60204, S-104 01 Stockholm, Sweden  
P.O. Box 100, A-1400 Vienna, Austria  
Direction générale,  
B.P. No. 6, F-92260 Fontenay-aux-Roses Cedex, France  
20 to 24 August 1984
CONSULTANTS MEETING
Vienna, Austria
27 to 31 August 1984

Farges, L.
Centre d’études nucléaires de Fontenay-aux-Roses,
B.P. No. 6, F-92260 Fontenay-aux-Roses, France

Groelsema, D.H.
Division of Uranium Mill Tailings Projects (NF-22),
US Department of Energy,
Washington, DC 20545, United States of America

Thomas, K.T.
International Atomic Energy Agency,
P.O. Box 100, A-1400 Vienna, Austria

(Scientific Secretary)
CONSULTANTS MEETING  
Vienna, Austria  
22 to 26 April 1985

Cook, J.E.  
Regulatory Bureau,  
Australian Atomic Energy Commission (AAEC),  
P.O. Box 153, Rosebery, NSW 2018, Australia

Farges, L.  
Centre d'études nucléaires de Fontenay-aux-Roses,  
B.P. No. 6, F-92260 Fontenay-aux-Roses, France

Groelsema, D.H.  
Division of Remedial Action Programs,  
UMTRAGRAP Group,  
US Department of Energy, NE-24,  
Washington, DC 20545, United States of America

Thomas, K.T.  
(Scientific Secretary)  
International Atomic Energy Agency,  
P.O. Box 100, A-1400 Vienna, Austria

Zgola, B.  
Atomic Energy Control Board,  
Waste Management Division,  
P.O. Box 1046, Ottawa, Ontario K1P 5S9, Canada
HOW TO ORDER IAEA PUBLICATIONS

An exclusive sales agent for IAEA publications, to whom all orders and inquiries should be addressed, has been appointed in the following country:

UNITED STATES OF AMERICA BERNAN – UNIPUB, 4611 F Assembly Drive, Lanham, MD 20706-4391

In the following countries IAEA publications may be purchased from the sales agents or booksellers listed or through major local booksellers. Payment can be made in local currency or with UNESCO coupons.

ARGENTINA Comisión Nacional de Energía Atómica, Avenida del Libertador 8250, RA-1429 Buenos Aires
AUSTRALIA Hunter Publications, 58 A Gipps Street, Collingswood, Victoria 3066
BELGIUM Service Courrier UNESCO, 202, Avenue du Roi, B-1060 Brussels
CHILE Comisión Chilena de Energía Nuclear, Venta de Publicaciones, Amunategui 95, Casilla 188-D, Santiago
CHINA IAEA Publications in Chinese:
China Nuclear Energy Industry Corporation, Translation Section, P.O. Box 2103, Beijing
IAEA Publications other than in Chinese:
China National Publications Import & Export Corporation, Deutsche Abteilung, P.O. Box 88, Beijing
CZECHOSLOVAKIA SNTL, Mikulandska 4, CS-118 86 Prague 1
FRANCE Office International de Documentation et Librairie, 48, rue Gay-Lussac, F-75240 Paris Cedex 05
HUNGARY Kultura, Hungarian Foreign Trading Company, P.O. Box 149, H-1389 Budapest 62
INDIA Oxford Book and Stationery Co., 17, Park Street, Calcutta-700 016
ISRAEL Heiliger and Co., Ltd, Scientific and Medical Books, 3, Nathan Strauss Street, Jerusalem 94227
ITALY Libreria Scientifica, Dott. Lucio de Biasio "aeiou", Via Meravigli 16, I-20123 Milan
JAPAN Maruzen Company, Ltd, P.O. Box 5050, 100-31 Tokyo International
PAKISTAN Mirza Book Agency, 65, Shahrah Quaid-e-Azam, P.O. Box 729, Lahore 3
POLAND Ars Polonia-Ruch, Centrala Handlu Zagranicznego, Krakowskie Przedmiescie 7, PL-00-068 Warsaw
ROMANIA Illexim, P.O. Box 136-137, Bucharest
SOUTH AFRICA Van Schaik Bookstore (Pty) Ltd, P.O. Box 724, Pretoria 0001
SPAIN Díaz de Santos, Lagasca 95, E-28006 Madrid
SWEDEN AB Fritzes Kungl. Hovbockhandel, Fredsgatan 2, P.O. Box 16365, S-103 27 Stockholm
UNITED KINGDOM Her Majesty's Stationery Office, Publications Centre, Agency Section, 11 Nine Elms Lane, London SW8 5DR
USSR Mezhdunarodnaya Kniga, Smolenskaya-Sennaya 32-34, Moscow G-200
YUGOSLAVIA Jugoslovenska Knjiga, Terazije 27, P.O. Box 36, YU-11001 Belgrade

Orders from countries where sales agents have not yet been appointed and requests for information should be addressed directly to:

Division of Publications
International Atomic Energy Agency
Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, Austria

This publication is no longer valid
Please see http://www.ns-iaea.org/standards/
This publication is no longer valid
Please see http://www.ns-iaea.org/standards/
This publication is no longer valid
Please see http://www.ns-iaea.org/standards/
This publication is no longer valid
Please see http://www.ns-iaea.org/standards/