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

A Code of Practice and Guide to the Code

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CORRIGENDUM

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

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

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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

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1976
FOREWORD

At the United Nations Conference on the Human Environment, which took place in Stockholm from 4 to 16 June 1972, governments were asked to explore with the International Atomic Energy Agency and other appropriate international organizations international co-operation on radioactive waste problems including the problems of mining and tailings disposal. Accordingly the Agency convened a panel meeting of experts in Ottawa from 8 to 12 July 1974 to review past and present waste management practices in the uranium and thorium mining and milling industry and to develop the background reference material required to formulate a Code for waste management in the industry. The text was completed by a second advisory group of experts which met in Vienna from 12 to 16 May 1975.

This book is in two parts. The first part is the Code of Practice approved by the Board of Governors of the International Atomic Energy Agency in June 1976 as part of the Agency’s safety standards, which are applied to those operations undertaken by Member States with the assistance of the Agency. The Board, in approving the publication of the Code, also recommended that Member States should take it into account in the formulation of national regulations and recommendations.

The second part of the book, the Guide to the Code, indicates ways in which the requirements of the Code may be met. This second part, although published under the same cover, is not part of the Code. The information in the Guide reflects current best available technology. This technology was considered by the advisory group to provide an acceptable degree of safety. Both groups of experts recognized that future developments might indicate that changes should be made in the degree of safety and environmental protection provided by the Code and Guide. Reviews and revisions should thus be published as and when necessary.

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PART I

CODE OF PRACTICE

1. INTRODUCTION

Wastes from the mining and milling of uranium and thorium ores can present a detrimental impact to man and his environment if proper waste management practices and controls are not adopted. This Code of Practice identifies those wastes which present environmental problems and sets out the minimum requirements for their competent management in a manner that adequately protects the public interest. The mining and milling of these ores have common problems with other mineral extraction operations but present additional health problems due to the radiotoxicity of the various radionuclides in the ore. When these radionuclides are incorporated in the body or externally irradiate it, they are capable of producing injury.

2. SCOPE

The Code considers from the environmental protection aspect the radioactive and chemical wastes arising from all stages of mining and milling operations (including in situ leaching operation) conducted with the primary or secondary objective of recovering uranium and/or thorium. It applies to all processes up to and including the production and packaging of the first uranium concentrate (normally 'yellowcake') and/or thorium concentrate (normally crude thorium nitrate, sulphate or hydroxide).

It includes the stabilization of waste retention systems, waste rock and heap leaching piles, the decommissioning of mines and mills, and the arrangements which should be made for their long-term control and maintenance. The Code does not consider the control of occupational hazards in mining and milling operations such as the reduction of radon and thoron concentrations in underground uranium or thorium mines, since this subject is already covered by an IAEA Code of Practice\(^1\).

Although the Code does not specifically deal with wastes from non-nuclear industries, the principles presented here can be adopted for the control of other wastes that may contain significant amounts of radioactive material, such as brown coal ash, by-product gypsum or phosphate residues.

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\(^1\) INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection in the Mining and Milling of Radioactive Ores, Safety Series No.26, ILO, Geneva (1968).
3. DEFINITIONS

The technical terms used in this Code have their accepted scientific meanings. The definitions of certain terms are as follows:

**Waste retention system**  
Storage system for liquid and solid wastes generated by the uranium or thorium mining and milling process.

**Liquid wastes:**

- **Mine drainage**  
  Water pumped or flowing from a mine.

- **Waste rock seepage**  
  Seepage from a waste rock storage area which may or may not contain environmentally significant materials.

- **Tailings seepage**  
  Seepage from a waste retention system.

- **Heap leaching seepage**  
  Seepage from an area where ore is or has been processed by heap leaching.

- **Barren solution**  
  Acid or alkaline leach liquor from which the recoverable uranium (and/or thorium, where applicable) has been recovered. This solution often contains reusable reagents.

- **Decant solution**  
  Solution which collects on, and is removed from, the surface of a waste retention system after the solids have settled out.

- **Final effluent**  
  Solution which is discharged from the controlled site.

**Solid wastes:**

- **Tailings**  
  These may be:
  (a) Mill tailings, which are the residues resulting from processing the ore in a mill to extract the metal values;
  (b) Heap leach residues, which result from treatment of ore by heap leaching.

- **Waste concentrates**  
  Any product (such as a settled sludge of Ba(Ra)SO₄ or the filter cake containing radium and lead from monazite processing) resulting from treatment performed to separate and concentrate the hazardous material.

- **Waste rock**  
  Material removed from the mine to allow extraction of the ore. This may be:
  (a) Barren rock containing essentially no metal values;
  (b) Low-grade material containing environmentally significant but not economically recoverable concentrations of uranium, thorium or other metals.
Embankment: A raised structure usually constructed as an earth dam to retain liquid and solid wastes. The embankment may be built using tailings, other materials, or a combination of both.

Pile: An above-ground deposit of self-supporting material not intended to retain water.

Heap leaching: The process whereby leach liquor percolates through a pile of ore formed on an impervious base 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 the place where it was originally deposited so that the leachate can be collected for recovery of the metal values.

Competent authority: A national or other authority whose jurisdiction applies to the protection of man and the environment from the activities of the mine and/or mill.

Manager: A duly qualified and appointed person responsible for the administration and direction of the mine and/or mill.

Owner: Any person, government or other entity that holds title to or owns the land upon which the mine, plant or other facilities are located.

Operator: Any person, government or other entity that conducts or carries on operations for the mining and/or milling of uranium or thorium ores.

Approved: Approved by the competent authority.

4. RESPONSIBILITIES

The manager and owner/operator should, at all times, be subject to the direction of the competent authority, and in particular should be directly responsible for:

(a) Preparation, for approval by the competent authority, of an assessment of potential environmental impacts of the wastes generated and released by the proposed mining and milling operation, including both the initial operation, any subsequent changes and decommissioning;

(b) Obtaining all necessary authorizations from the competent authority including those for disposing of wastes (as identified in this Code) and the environmental monitoring programme;
(c) Establishing and implementing approved effluent release controls and environmental monitoring programmes including pre- and post-operational surveys and keeping all necessary records;
(d) Ensuring that all waste disposal operations are carried out in accordance with such authorizations and approvals;
(e) Assessing the consequences of unplanned events which may release additional wastes to the environment, developing approved emergency plans to deal promptly with such events, implementing the plan if such an event occurs and promptly reporting the event and the action taken to the competent authority;
(f) Stabilizing by approved methods the waste retention systems, waste rock and heap leach piles during both the operational phase and after operations cease, and taking such other actions as may be deemed necessary by the competent authority;
(g) Planning the decommissioning of the mine and/or mill site, obtaining all necessary authorizations from the competent authority and performing the work in accordance with such authorizations; and
(h) Carrying out such inspections and keeping such records as may be required by the competent authority.

The competent authority is directly responsible for:

(a) Regulating and controlling the activities of, and giving appropriate direction to, managers and owners/operators;
(b) The prompt review of all proposals submitted by the manager/owner/operator as required by this Code and the issuing of discharge and other authorizations to ensure the protection of the public and the environment. In particular, the level of protection of individuals and the population against the effects of ionizing radiation should comply with the current recommendations of the International Commission on Radiological Protection (ICRP);
(c) Regulating and inspecting the waste management operations and records to ensure that the authorizations are being complied with; and
(d) Assessing the consequences of any unplanned event which caused the release of waste in excess of the authorization and advising the manager/owner/operator of any remedial action which may be necessary to limit the effect of the release and/or prevent a recurrence.

5. ENVIRONMENTAL CONSIDERATIONS AFFECTING SITING AND DISCHARGE LIMITS

The environment at the site of the mine or mill has a very great influence on the requirements for successful waste management. The major site characteristics which affect the selection of waste retention sites and waste management practices are climate,
the magnitude and frequency of floods, geography, topography, demography, geology, 
seismicity, hydrology, mineralogy (of ore, rock and embankment foundations), flora 
and fauna and the revegetation potential.

Uranium and thorium ores were formed by concentration, in selected zones, of 
uranium and thorium naturally present in the earth. The local concentration of uranium 
and thorium in mineralized formations has a limited regional impact on natural levels of 
radiation, which vary appreciably from place to place.

Authorized limits for discharge of effluents should be fixed in each case by the 
competent authority, which will take into account the radioactive and chemical com­
ponents of the effluent, the characteristics of the environment, and the ICRP recom­
mendations, which aim to limit radiation exposure of the critical group of the concerned 
population to values below the fixed limits and to optimize protection, maintaining all 
exposures due to the release as low as is reasonably achievable.

The aim of environmental monitoring should be to check whether approved proce­
dures and regulations have been followed, to ensure that nothing unforeseen has happened, 
to ascertain that individuals are not and are not likely to be exposed to contaminations in 
excess of approved limits and to indicate whether discharge authorizations should be 
redefined.

6. WASTES REQUIRING MANAGEMENT

This section discusses those wastes from uranium and thorium mines and mills that 
can present a detrimental impact to man and the environment and thus require manage­
ment in accordance with the authorizations granted by the competent authority.

It must be clearly understood that mine and mill wastes containing radioactive 
material should under no circumstances be used as construction material in buildings 
or as a fill underneath or around habitable structures.

6.1. Mine wastes

6.1.1. Solid wastes

(a) Waste rock

Barren rock. This material normally does not present an environmental contamination 
impact and may thus be disposed of in accord with the general requirements below.

Low-grade material. This material may present an environmental contamination 
or radiological impact if stored on the surface. Thus the mineralogy of the rock 
should be assessed in relation to the site characteristics before deciding on the 
method of disposal to be adopted. Disposal in the mine may reduce the potential 
impact and may be preferable if the radiological protection, hydrogeological,
engineering and economic aspects are favourable. The effects of seepage should be monitored and assessed, and provision for collection and treatment should be made if required.

General requirements. Waste rock piles should be sited and constructed with due regard to site characteristics, engineering and aesthetic criteria. Potential problems caused by wind and water erosion should be taken into account. Consideration should also be given at the planning stage to the requirements to be met when the mine is closed down.

(b) Scrap material and equipment

When the radioactive surface contamination level exceeds the limit approved for unrestricted disposal, even after decontamination steps have been taken, this material should only be disposed of in accordance with approved procedures.

6.1.2. Liquid wastes

Liquid wastes include the levels of chemical substances and radioactive nuclides in drainage and seepage waters which should be monitored and assessed. If the levels exceed the approved permissible levels for unrestricted discharge, these waters should be recycled to the mill, discharged to a waste retention system or treated in accordance with approved procedures.

6.1.3. Airborne wastes

Exhaust ventilation from underground mines should be controlled so that individuals and the public are not exposed to unacceptable levels of radon or dust.

The release of dust from all mining, transport and storage operations should be reduced to the lowest practicable level in accordance with approved procedures.

6.2. Mill wastes

6.2.1. Solid wastes

Tailings. The goal in management of tailings is their disposal in such a manner that continuing surveillance (over thousands of years) would be reduced to a minimum, if not made unnecessary. This goal has not yet been achieved, but in view of its feasibility in some cases, it should be striven for when planning each new project. However, there are alternatives for managing tailings in a safe manner.

If the hydrogeological, engineering, radiological protection, environmental and economic aspects are favourable, disposal to mined-out areas is preferred. However, at least for underground workings, it is rarely possible to arrange for all the tailings material
to be so disposed, and a surface waste retention system for the remaining fine material is still needed.

The more usual solution involves the construction of a waste retention system to retain the tailings material in such a manner that it does not present an unacceptable risk, either now or in the future, to man and the environment beyond the immediate area of the deposit, with due account being taken of wind and water erosion and radon emanation.

The characteristics of the tailings, including factors affecting long-term stability, should be assessed in relation to the site characteristics before selecting the waste retention system to be adopted and the water management programme which is a part of it.

The site assessment should involve field measurements of the permeability of the base of the waste retention system and of the material to be used in the construction of the embankment. Unstable material should not be used in the embankment. Geological fault zones should be identified and avoided where indications of instability exist. Consideration should be given to reducing their permeabilities by grouting or other means, where necessary, and to locating test bores in aquifers and fault zones as a check on the estimates for seepage loss.

The design and construction of the embankment system should meet the safety criteria of engineering codes with respect to long-term stability, particularly against internal and external erosion and seismically induced acceleration fields. Consideration should be given to operating systems as well as requirements for decommissioning.

The embankment design should provide adequate free board at all times, means for preventing wave erosion of the upstream face and physical protection of surfaces that is consistent with the long-term objectives of stabilization.

*Heap leach piles.* The design of heap leach piles should include factors related to the management of the pile at the end of its economic life. If seepage from the pile could cause a continuing environmental problem then appropriate preventive actions should be taken.

*Waste concentrates.* Waste concentrates can contain relatively high concentrations of radionuclides, so their final disposal should be carefully assessed and carried out only after authorization of the competent authority.

*Scrap material and equipment.* When the radioactive surface contamination level exceeds the limit approved for unrestricted disposal, even after decontamination steps have been taken, scrap material and equipment should only be disposed of in accordance with approved procedures.

6.2.2. Liquid wastes

Liquid wastes normally produced in the milling of uranium and thorium ores include barren solution, decant solution, tailings seepage and heap leaching pile seepage
as well as plant washings and laboratory wastes. The potential impacts of these wastes should be assessed and suitable treatment and/or disposal practices should be adopted, as approved by the competent authority.

The discharge or release of the final effluent into surface and underground waters should be minimized by restricting the use of fresh water and by maximizing the recycle and reuse of the liquid wastes in the process. When liquid wastes cannot be reused in the operation because of the dissolved solids content, local treatment systems to permit such reuse should be established where required. It is preferable to recycle liquid wastes to the plant to the greatest extent practicable, or to use them to slurry solid tailings being discharged to the waste retention system. In areas where the natural rate of evaporation exceeds the rainfall, the waste retention system may be designed with sufficient surface area so that no discharge of liquid wastes from the site is required. In areas, however, where this cannot be done because the rainfall exceeds evaporation, sufficient area should always be provided to permit settling of solids before the liquid is decanted.

For those liquid wastes which cannot be used in the process or retained on site, suitable treatment procedures should be employed to reduce contaminants. The quality of the final effluent that may be released from the site should be monitored, assessed and approved by the competent authority.

6.2.3. Airborne wastes

All processes generating dust and fumes should be provided with approved exhaust ventilation systems. Approved filters, scrubbers or other devices should be fitted to reduce the discharge of airborne contaminants as far as practicable and the discharge should not exceed approved limits. Recovered material should be returned to the process. Measures should be taken to minimize sources of airborne waste.

6.3. In-situ leaching wastes

In-situ leaching operations may generate some liquid and solid wastes, such as filter sludge, that can be treated by approved methods.

Special attention should be given to developing approved operational controls and procedures to prevent or limit the infiltration of leach solutions from the leach site into fresh water aquifers.

When leaching operations are completed, special attention should be given to utilizing approved procedures to elute the remaining leaching solution and restore the site to approved hydrological and chemical conditions.

7. DECOMMISSIONING REQUIREMENTS

At the end of the useful life of the mine or mill, safety considerations require that certain actions should be taken to decommission the site. Since these actions are taken
to ensure that releases of radioactive and toxic material are within approved limits, and to reduce radiation exposures, they are included here.

It is expected that some land will, after decommissioning, be subject to a covenant restricting future use of the land. The land areas for which restrictions are necessary should be minimized to the extent practicable by the use of proper practices during operation and decommissioning.

7.1. Mines

Underground mines. An underground mine should be sealed and plugged in accordance with normal mining requirements. Additional actions may be required by the competent authority in individual situations to control radioactive nuclides and other contaminants released from the decommissioned mine so as to prevent pollution of aquifers and surface waters.

Open cut mines. With open cut mines the banks of the open cut should be left in a safe condition in accordance with normal mining requirements. Additional actions may be required by the competent authority in individual situations to prevent pollution of aquifers and surface waters.

Contaminated plant and structural material. All items of plant, equipment and structural material contaminated with radioactive material should be decontaminated to or below the approved level before they can be removed from the site. Alternatively they may become another type of solid waste and should be disposed of in accordance with approved procedures.

Contaminated areas. All areas contaminated with radioactive material except the mine itself and the waste rock piles should be decontaminated to the approved level. Soil scrapings can be returned to the mill for processing.

Waste rock piles and waste retention systems. Waste rock piles and waste retention systems should be left in a completely stable form so that they blend aesthetically with the general landscape. The piles should be returned to an appropriate land use by revegetation or by other means. Appropriate measures should be taken to protect the public from any hazard presented by the piles.

7.2. Mills

Contaminated plant and structural material. All items of plant, equipment, and structural material contaminated with radioactive material should be decontaminated to or below the approved level before they can be removed from the site. Alternatively they may become another type of solid waste and should be disposed of in accordance with approved procedures.
Contaminated areas. All areas contaminated with radioactive material except the waste retention system and heap leach sites should be decontaminated to or below the approved level.

Waste retention systems and heap leach sites. Waste retention systems and heap leach sites should be stabilized in an appropriate manner so as to preclude wind and water erosion resulting in release of waste materials in excess of applicable approved standards. Stabilized areas should be protected against run-off from surrounding drainage areas by provision of diversion channels. Consideration should be given to potential effects of precipitation on the integrity of the stabilized area and the possible seepage from the stabilized area.

Stabilized areas should be controlled and posted so as to restrict public access and habitation and to prevent the unauthorized use of tailings. In adjacent environs accessible to the general public, radiation levels and radon emanation from the stabilized waste materials should not exceed applicable approved standards. A surveillance and monitoring programme should be established to determine when maintenance is necessary and to determine environmental concentrations of radioactive and other waste materials.

The proposed plans and programmes for dealing with the tailings, including any proposed use of the stabilized area or the tailings themselves, should be approved before implementation.

8. FINANCIAL ARRANGEMENTS FOR MAINTENANCE AND MONITORING OF MINES, TAILINGS AND HEAP LEACH AREAS AFTER DECOMMISSIONING

The owner/operator should establish approved financial arrangements (e.g. bonding, escrow accounts) to ensure that there are sufficient funds to carry out the maintenance and monitoring programmes.

9. PERIODIC INSPECTIONS OF WASTES AND THE ENVIRONMENT

9.1. Inspection during operation

The manager should ensure that inspections and monitoring, including sampling and analysis, are carried out to determine that approved waste management practices are being followed. Reports of such inspections should be prepared and circulated as required by the competent authority.

9.2. Inspection after decommissioning

The owner/operator of the decommissioned site should ensure that inspections and monitoring, including sampling and analysis, are carried out to determine that all
applicable requirements are being met. Reports of such inspections should be prepared and circulated as required by the competent authority.

10. TRANSFER OF OWNERSHIP

The seller of land affected by uranium and/or thorium mining and milling wastes should fully inform the buyer and the competent authority of the nature of the wastes. The competent authority should inform the buyer of his obligations for maintenance and control, and the buyer should assume these obligations when such sale is effected.
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PART II

GUIDE TO THE CODE

1. INTRODUCTION

The aim of this Guide to the Code is to provide guidance to those responsible for implementing the requirements of the Code. This is done by describing the wastes which arise from the mining and milling of uranium and thorium ores, by discussing the radiological and environmental protection problems which they raise, by describing waste management practices which have been found by experience to give a satisfactory solution and by proposing possible solutions which warrant evaluation during the planning stage of new operations. For ease of reference the sections in the Guide correspond to those in the Code.

2. SCOPE

Although there is no such thing as a typical mine or mill, the Code has been written to cover current or planned operations. It is believed, however, that it is sufficiently general to apply to unusual sources of uranium and thorium and to unconventional processing methods.

Uranium is present in the earth's crust at an average value of 4 g U/t. This may be compared with the values for known deposits, currently extracted ores, which range from 150 g U/t (from which uranium is extracted as a by-product) to 400 kg U/t in selected areas of rich deposits. Large shale deposits under consideration for mining contain about 300 g U/t. Ores mined at present generally have a range of 0.5 to 10 kg U/t.

Uranium ores are mined by both open cut and underground methods. In special situations, uranium may be extracted by an in-situ leaching operation. The mining method adopted is generally chosen solely on the basis of the mining aspects of the ore deposit without taking consideration of waste management aspects, although the cost of radon control in underground mines may influence the decision towards open cut operation [1]. The mining operations are similar to other mining operations of a similar size, except that radiological protection requirements sometimes impose additional constraints. The wastes originating from the mining stage are as follows:

- Waste rock, and scrap material and equipment;
- Mine drainage and seepage from ore storage and waste rock piles;
- Exhaust ventilation from underground mines, and from ventilated equipment such as tipples, crushers, conveyors.
The mined ore is transported to the mill, where it is normally treated by one of the processes shown in Fig. 1 to recover a crude uranium concentrate, 'yellowcake'. Details of the various processes and flow sheets are not given here as they are well known and reported in the literature [2, 3]. The wastes which originate from the milling stage are:

- Solid wastes consisting mainly of mill tailings from the extraction process, together with contaminated scrap and junk;
- Liquid wastes consisting mainly of acidic or neutralized barren liquor from acid leach plants or the water used to transport the tailings in the case of alkaline leach plants, plus small volumes of other liquid wastes such as floor washings, laboratory wastes;
- Seepage from waste retention systems and heap leaching piles;
- Decant solution from waste retention systems;
- Contaminated run-off from plant area;
- Airborne dusts from conveyor transfer points, tipples, coarse crushing, reagent preparation and product drying/calcining operations;
- Airborne mists and fumes from reagent preparation and leaching operations;
- In-situ leaching operations may generate some liquid and solid wastes such as filter sludge.

Thorium mining generally takes the form of dredging or excavating beach sand or placer deposits containing monazite, and is often associated with the recovery of rutile, zircon and ilmenite. These heavy minerals are generally concentrated by wet gravity

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**FIG. 1. Uranium ore processing methods.**

separators (spirals, jigs and tables) and by dry wind tables and electrostatic and electromagnetic separators to yield relatively high-grade concentrates of the above minerals.

The only waste which has to be considered is dust from the dry separation processes since the sands and gravels are generally returned to the area from which they were extracted in virtually the same state that they were in before treatment. Since the minerals are insoluble, the water used in the wet separation plant is not contaminated with chemicals or radionuclides.

Some thorium ore has been extracted by underground mining operations [4] that are comparable to those used for uranium, except that the ore is generally of a higher grade and this poses greater radiological protection problems. The wastes arising from these thorium operations are of the same types as those from uranium mining.

At present most thorium is recovered from monazite. The treatment process adopted in India is as follows.

Monazite with a typical composition of 9.5% ThO₂, 28% P₂O₅, 60% rare earth oxides, and 0.3–0.4% U₃O₈, is ground and treated by alkali digestion to obtain the hydroxides of thorium and rare earths and to separate trisodium phosphate. Controlled leaching of the hydroxides by hydrochloric acid separates the rare earths from the thorium. Rare earth chloride so produced is marketed as such, or further processed to separate individual rare earths by solvent extraction. According to the final product required, the thorium hydroxide may be further treated by hydrochloric acid and then converted to sulphate and hydroxycarbonate before final conversion to thorium nitrate. Alternatively, a solvent extraction route using tributyl phosphate is available for making nuclear-grade thorium oxide. Uranium streams from the thorium separation stage are further processed by conventional methods for producing nuclear-grade uranium.

Air contamination occurs in the monazite grinding stage. Some of the other operations in the process, such as the filtration and drying of thorium concentrates and the evaporation of the rare earth chloride, also give rise to air contamination. Radioactive liquid wastes produced in the rare earth and thorium separation processes consist of filter press and other washings and coolants and total about 60 m³/day. Solid wastes consist of filter cake or sludge from purification steps and scrapped filter cloth and equipment.

At various times since uranium mining and milling operations began in Canada there have been periods during which thorium recovery has been carried out. During acid leaching as carried out in the Elliot Lake area approximately 80% of the thorium is leached from ore containing from 0.025 to 0.05% thorium. This has been recovered by means of solvent extraction from uranium recovery ion-exchange effluents, barren of uranium but containing a significant thorium concentration.

When thorium recovery is not in progress the barren solution containing thorium is recombined with the solid tailings from uranium operations and discharged to the waste retention system after the normal neutralization to pH 10–11. Thorium is precipitated at this pH and is retained with the tailings solids.
3. DEFINITIONS

Because of the variations in terminology used in different countries, standard terms have been adopted to the extent possible, and these have been defined in the Code. The term ‘waste retention system’ has been taken from an existing standard [5], and replaces such confusing terms as ‘tailings dam’, ‘tailings pond’, ‘tailings embankment’, ‘tailings pile’ etc. However, the terms ‘active’ and ‘inactive’ used in the above standard were not considered acceptable because of possible confusion with their alternative meanings of ‘radioactive’ and ‘non-radioactive’, and it was considered that ‘operational’ and ‘non-operational’ were preferable when it was necessary to distinguish between the two states.

The definition of ‘operator’ is included to provide for the situation where a mining company does not have title to or any ownership of the land on which it is carrying out operations.

4. RESPONSIBILITIES

The responsibilities for waste management may vary considerably from country to country, but it is believed that the basic approach adopted in the Code should be capable of being implemented in any situation.

The division of responsibility between the manager and the owner/operator has not been strictly identified as it is considered that this may vary from one situation to another, according to the type of ownership, amount of Government participation, etc. The competent authority should evaluate this situation and clearly establish where the responsibilities lie. In general, it appears to be common practice that the manager is responsible during the operational phase, and that the owner/operator assumes responsibility after the sites are decommissioned.

Where the actual operation is being conducted by an ‘operator’, it is essential that the ‘owner’ be made fully aware of the probable extent of his future obligations so that he can negotiate such agreements with the operator as are necessary to protect his interests.

Guidance on the preparation of environmental impact assessments is available in References [6, 7]. The objectives and design of environmental monitoring programmes for radioactive contaminants are given in References [8, 9].

With regard to the need to develop emergency plans, the only waste management emergencies that can be envisaged which may have more than transitory effects are a large release of tailings or waste concentrates. As there have been many instances of waste retention systems failing, it appears advisable to have emergency plans ready to implement, to limit the effects of such a failure.

However, as the unplanned failure is most likely to occur during or immediately after heavy rainfall when run-off and stream flow rates are high, it may well be that the emergency action that can be taken will do very little to limit the extent of the resultant
contamination. All that may be achieved is prompt repair of the embankment or dam and prevention of further spread of the wastes.

To prepare a realistic emergency plan, several possible unplanned events should be studied and their potential effects assessed. The plan should take into account such matters as the availability of material suitable for repairing an embankment, the availability of equipment to transport it and put it in position, the location of possible sites to build embankments to hold the tailings already lost from the waste retention system, and methods for collecting the lost material.

In studying potential unplanned events, it may be possible to implement design or operational changes that would significantly reduce the possibility of such events happening. This may be the best form of emergency planning — to further reduce the probability of an unplanned event.

It is essential to the achievement of their common goal, the safe and economical management of waste, that the relationship between the regulatory body and the operating organization should be based on mutual understanding and respect. Consequently the operating organization should regard the regulatory body 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.

5. ENVIRONMENTAL CONSIDERATIONS AFFECTING SITING AND DISCHARGE LIMITS

5.1. Climate

Precipitation, especially when considered with the annual evaporation at a site, virtually decides 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. If the average annual evaporation exceeds the average annual precipitation, and assuming zero or estimated seepage losses, 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 magnitude and frequency of floods must be considered when siting a waste retention system, as it is generally unwise to site a system on a site that may periodically be subject to flooding.
The rate of rainfall is also important since it determines the loss of material from wasterock piles, ore storage piles and the waste retention system as a result of erosion. Disaggregation of the surface soil peds and the initial detachment of particles is the work of raindrop impact. Under intense rainfall, the surface peds break down and particles are ejected and carried away as sheet erosion. The drier the soil and the fewer the pores, the greater the pressure exerted by air entrapped during wetting. Maximum breakdown occurs when very dry soil is rapidly flooded by intense rain. Vegetation therefore serves to protect the soil surface from the adverse effects of extreme dryness, rapid submergence in water and raindrop impact.

Fluvial erosion increases rapidly with stream velocity. For mining developments in areas with heavy winter snowfalls, diversion channels and site drainage systems have to be designed to meet the peak discharges that can occur during the thaw.

The diurnal and seasonal fluctuations in surface ground temperatures also influence waste management. In permafrost areas, the stabilization of tailings by revegetation is almost impossible. However, if ground temperatures are low enough, bacterial oxidation of sulphide minerals is suppressed. In warmer climates, the diurnal temperature cycle can be a significant mechanism for the transportation of oxygen into tailings and waste rock material with a resulting increase in bacterial leaching.

The inversion characteristics of the mine and mill sites are an important parameter. A knowledge of the frequency, duration, strength and break-up interval for atmospheric inversions is needed for the calculation of the concentration at the plant and town site 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$_2$ damage to vegetation and the exposure of the general population during fumigation conditions.

5.2. Geography

This factor also has a large influence on the waste management practices adopted at a particular site. For instance the topography may not allow the construction of large tailings embankments, or permanent rivers may not be available to dilute effluent discharges. Adjacent farms, towns, or cities may impose additional constraints. The present and potential land use for terrestrial and aquatic food production determines the dose commitment that would stem from the discharge of a given quantity of radioactive material. The age, diet, and recreational and working habits of the local inhabitants determine the characteristics of the critical group used for radiological calculations.

5.3. Geology

The geology of the orebody generally dictates the choice between open pit or underground mining, and the decision has some effects on waste management. Open pits, for example, generally collect more rainfall than underground mines, and this collected water may have to be handled as liquid waste. Some underground mines in
weak ground require backfilling for stabilization. This backfill material can comprise the sand portion of the tailings, thus reducing the amount of tailings requiring surface disposal. However, the high proportion of fines in the remaining fraction increases the difficulty of building a waste retention system and ensuring its stability.

The geology of the area also influences selection of the site for an 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 tailings material resting on a dolomite bed.

The seismicity of the area must also be considered when siting and designing an embankment, since earthquake deformation and possible consequent liquefaction due to earthquake shocks can have serious consequences.

5.4. Mineralogy

The mineralogy of the ore and the host rock influences the nature and degree of the waste management problem. The major world reserves and resources of uranium have been found in a relatively few geologic ore types. These include sandstones, the principal host rock in the United States of America, Niger and Gabon, while quartz pebble conglomerates are the principal source of uranium production in Canada and South Africa. Vein-type deposits are also major sources of uranium, principally in Australia, Canada and France. Although not sources of uranium production now, low-grade uraniferous shales occurring in Sweden, Spain and the United States represent a major resource which may have to be exploited in the future. Recovery of uranium as a by-product from phosphate rock and porphyry copper ores is to be expected in the near future, but will be a relatively minor source, limited by the rate of production of the primary product.

The uranium mineralization in various ores is well documented and needs little elaboration here. 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.

Nevertheless, it is frequently difficult to find quantitative information on gangue mineralization and its relationship to the problems of extractive technology and waste management. Characteristically, uranium-bearing minerals are considerably softer than the quartzites and silicate minerals that comprise the bulk of the gangue. In the crushing and grinding operations, the uranium, vanadium, radium and other minerals of interest tend to be reduced to fine slimes and mix with the clays and other sub-micron size particles. Therefore the handling of the slime portion of the ore is of disproportionate importance in milling and in waste management practices.

**Sandstone ores**

The uranium mineralization generally occurs as surface coatings on sand grains. The sands are cemented to varying degrees by clay minerals, mudstones and limestone.
The ores almost invariably contain small amounts of organic materials, but little or no pyrite or other sulphides. Alkaline leach processing may be necessary if the limestone content of the ore is high, above 10–15%. Otherwise, acid leach processing is usually employed. The clay minerals, which disperse as a fine slime during the grinding operations, represent a major handling problem. The slimes control the rates of filtration and thickening, and complicate tailings disposal operations as they concentrate in the centre of the waste retention system and remain in a fluid state indefinitely. Small concentrations of molybdenum and vanadium and to a lesser extent selenium, which are present in almost all sandstone ores, are solubilized to some extent during leaching and may require special attention.

Quartz pebble conglomerates

The conglomerate ores are remarkably continuous over large areas. The orebody itself consists of quartzite pebbles interbedded with fine quartz, sericite and chlorites. In Canada the ores contain about 4–8% pyrite and in South Africa about 2–5%. The Canadian ores contain thorium, usually in a concentration about one-third that of the uranium. Gold is absent from Canadian conglomerates but is the major economic mineral in South African conglomerates, with a few notable exceptions in which the ore is relatively high in uranium content and too low in gold to be mined for gold alone. The conglomerate ores require fine grinding (60 to 80% — 200 mesh) to expose the minerals to leaching reagents. Nevertheless, the ore after leaching is readily filterable, and contains a relatively small proportion of fine slimes when compared with sandstone ores. The high pyrite content of these ores represents a major waste management problem, as it oxidizes gradually in the tailings, creating sulphuric acid and high sulphate concentrations. The problem of pyritic tailings is compounded if other heavy metals such as copper and zinc are also present as sulphides, which can be oxidized and leached from the tailings. The generated acidity also makes the revegetation of sulphide tailings more difficult. The low slime content results in a porous tailings material, and, where rainfall is substantial, an acidic drainage from the tailings area.

Vein-type deposits

Vein-type deposits are highly variable in nature and extent. They may contain massive pitchblende, such as was found at Shinkolobwe in the Belgian Congo, and at the Eldorado Mine on Great Bear Lake in Canada. Found in fault zones in various host rocks, the gangue materials are difficult to categorize. Generally, however, they contain sulphide minerals in significant quantities; they may also contain appreciable amounts of limestone. Consequently, a variety of processing methods are used, including acid leaching, alkaline leaching, and even flotation to isolate a sulphide concentrate for separate treatment.
Soils and waste rock

The mineralogy of soils and the subsurface of areas under consideration for mill sites and waste retention systems deserves greater attention than it has 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 tailings contain sulphides that can be expected to generate acid. Continuing acid percolation into the subsurface can dissolve alkaline rocks, opening channels for solution loss from the site, and also possibly affecting the stability of the waste retention system.

Waste rock may contain minerals which interact after being broken up and exposed to the atmosphere. For example, a mixture of iron pyrites and ankerite can generate soluble manganese waste by ferrous iron substitution.

5.5. Hydrology

The hydrology of the area influences the amount of water infiltrating into the workings and in some cases into the waste retention system, and controls the length of time that the water is in contact with the ore. This in turn influences the composition of the mine drainage and tailings seepage and affects their disposal.

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 containing non-potable water. This decision is affected by the existing and potential uses of groundwater in the area.

5.6. Flora and fauna

The nature of aquatic and terrestrial habitats influences the degree of environmental degradation that would result from inappropriate waste management. Siltation can cause loss of fish breeding grounds and reduce egg hatchability. Discharged 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 are more sensitive, the softer the water. Discharged tertiary amines reduce phytoplankton productivity, the effect being more marked if kerosene is also present. Thus fairly minimal waste discharges can upset the local ecosystems and produce substantial changes in the diversity of species. This in turn can reduce the commercial and recreational value of the waterbody.

Water quality also influences the bioaccumulation factor of aquatic organisms for radioactive and non-radioactive heavy metals. These factors need to be taken into account when assessing the radiological impact for members of the critical group.

The soil-pasture-stock transfer mechanism determines the capacity of the terrestrial environment for heavy metal wastes. Antagonistic effects exist for Cu and Mo, and metals such as V and Sc can be concentrated in some perennial grasses.
5.7. Revegetation potential

The reclamation of waste retention systems by revegetation is affected by many of the characteristics already discussed.

Selection of plants for revegetation must take into account climatic conditions including temperature, length of day, insolation, length of growing season, presence of permafrost, amount and distribution of rainfall and prevailing wind direction and velocity.

The mineralogy of the ore and the milling process determines the pH of the tailings, their salinity, particle size, toxic metal content, plant nutrient content, aggregation, and water retention characteristics. The mineralogy of waste rock has similar effects on waste rock piles.

6. WASTES REQUIRING MANAGEMENT

6.1. Mine wastes

6.1.1. Solid wastes

(a) Waste rock

It must not be overlooked that mine waste rock requires management during the early development, operation, and closing of any uranium or thorium mine. The material originates from the removal of rock in order to provide access to the ore. The quantity may range from one-tenth of the processed ore for well situated underground mines to 30 times the processed ore for some new pits now in operation. The quantity and proportion will undoubtedly increase as less favourably situated ore bodies are worked to meet future demands. These materials are normally brought to the surface in underground mines, or result from the stripping of overburden in open cut mines. Before rejection the waste may be treated by electronic sorting, washing or screening to recover any economic grade material. At present no uniform method of waste management is employed for waste rock.

The characteristics of waste rock are frequently more variable than the orebody itself since the material may originate in the surrounding or overlying rock with little or different mineralization, or it may be a portion of the orebody 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 on any of the following uses:
- As a source of uranium which can be recovered by heap leaching;
- To refill the workings, especially open pit mines;
- For construction of embankments on the mine site;
- For construction of diversionary structures to divert run-off and water course streams away from waste retention systems.
For construction of roads, and similar filled projects on the mine site;
For sale for off-site use.

Different restraints exist for each possible utilization for waste rock. For example, its return to open pits is only a suitable alternative if the open pit has not been developed through aquifers and/or if the waste rock does not contain active sulphides. Similarly, it must not be sold for off-site use if it will contribute significantly to the radiation exposure of the population or have any other significant environmental or public health effect.

If waste rock is subject to heap leaching to recover uranium, then the extracted heap becomes a waste which presents some problems due to the residual radium content. Care should be taken, when siting and constructing such heaps, to minimize their eventual impact.

Because it isolates the material from the external environment, disposal of waste rock 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, they should be located to minimize environmental impacts and to ensure mechanical stability. They should be constructed according to engineering codes using sound engineering practices. Consideration must also be given at the planning stage to the requirements to be met when the mine is closed down. Guidance for the designing of waste rock piles is given in Reference [10].

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 (Section 6.1.2).

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 steepsided except for the approach road and will exhibit a low run-off 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.

Heap leaching piles are necessarily constructed so that the drainage from them can be collected and treated (generally in an existing mill) for recovery of uranium. The leaching solution is generally recirculated or, after extraction of uranium, is released with other liquid effluents. However, long after it is economic to recover the uranium, rain-water will seep through the pile and, according to the mineralogy of the ore, may continue to extract small quantities of such metals as uranium and radium.

During the operational mining phase, piles that are a potential source of pollution can be centrally drained and the waste stream treated. Practical and economic solutions have not yet been found for all non-operational piles. The problem may be more severe in areas that have a marked seasonal or heavy rainfall since the potential for bacterial leaching is greatly increased. The possibility also exists that vegetation on the pile and in
its surroundings could contain levels of heavy metals and/or radioactive materials that would be toxic to grazing animals or present a public health problem.

(b) Scrap material and equipment
In mines with ore grades below, say, 1% uranium or thorium it is unlikely that scrapped material and equipment would have radioactive surface contamination levels that would require this material to be classified as radioactive waste. Where higher-grade ores are being worked, however, scrapped drilling, digging, loading, transport and other equipment may become contaminated to the extent that it should not be disposed of with the normal scrap and junk.

Valuable equipment in this category may be decontaminated if required for use elsewhere, 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 as it does not have the potential to add significant radioactive contamination to the environment. 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 and finally covered to a depth of at least one metre.

6.1.2. Liquid wastes

Mine drainage. Mine drainage consists mainly of surface water or groundwater which has entered the workings through subterranean channels or fissures, or rain-water 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 should be reduced, to the fullest extent feasible, by:
- reuse of water in the mine for drilling and dust suppression;
- 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;
- treatment of water underground for reuse. 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 drainage, all practical 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;
— minimization of hold-up and possible oxidation of broken sulphide within the mine
so as to decrease the opportunity for acid generation and metal dissolution.

Mine water can contact the orebody 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), as indicated in Table 1. In underground
mines where it may contribute appreciably to radon levels in mine air, it should be collected
as soon as possible and piped to the surface. 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. This is common practice in
Canada.

If more drainage 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 dis­
charge it under controlled conditions to surface waters or a confined aquifer, after treat­
ment if necessary. Specific treatment and disposal of a mine drainage waste stream is
dependent on local conditions such as the mineralogy of the orebody, climate, topo­
graphy 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, lime neutralization, ion exchange, precipitation with barium salts, and
scrap ion cementation processes.

In Czechoslovakia some water from uranium mines is treated before discharge. In
one case radium-contaminated pit waters of low salinity are purified at a rate of 10 m³/min
by cation exchange resins in columns. The resins are regenerated by using a salt solution,
which in turn is decontaminated by either finely crushed barytes, a radium-selective
sorbent based on activated barium sulphate, or by coprecipitation in mixer settlers.
The decontamination factor for this process is about 10 and the volume reduction factor
\[
\frac{\text{Effluent treated}}{\text{Dry concentrate}}\]
is 10⁶.

Also in Czechoslovakia, research has been continuing on the problem of removing
radium from effluents and furthermore on the possibility of removing it from water
supplies.

The developmental and research work is predominantly focused on selective sorbents,
the synthesis of chelating resins, and the use of reversible organic gel exchangers such as
sulphonated cross-linked styrenes.

Radium-selective sorbents based on activated barium sulphate cannot be used in a
conventional sorption column as they undergo structural changes leading to the deteriora­
tion of their sorption properties. For such fine-grain or powder-like sorbents a clarifier
type of sorption contactor has been built and tested.

A two-stage process and installation was experimentally verified on a large scale.
The radioactive waste flowed upwards through a suspended bed of a rapidly sorbing
### TABLE I. SOME POTENTIAL CONTAMINANTS IN LIQUID WASTES

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Mine drainage</th>
<th>Decant solution and tailings seepage</th>
<th>Decommissioned mine drainage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acid</td>
<td>Basic</td>
<td>Acid</td>
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<tr>
<td><strong>Radioactive</strong></td>
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</tr>
<tr>
<td>$^{226}$Ra</td>
<td>+</td>
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<tr>
<td>Rn</td>
<td>+</td>
<td>+</td>
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<tr>
<td>$^{210}$Po</td>
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<td>$^{220}$, $^{222}$Th</td>
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<td>$^{210}$Po</td>
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<td><strong>Non-radioactive</strong></td>
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<td>$\text{H}_2\text{SO}_4$</td>
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<td>Cl</td>
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<td>NO$_3$</td>
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<td>Ca</td>
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<td>Mg</td>
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<tr>
<td>Kerosene, alcohol, amine, TBP</td>
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<tr>
<td>Oil (lubrication or fuel)</td>
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* + = potential contaminant.
and regenerable cation exchanger maintained partially in a turbulent state (lower section) and partially in a quiescent state slightly under the flotation threshold (upper section) in a conical contactor. The saturated bed of the sulphonated copolymer styrol-DVB was periodically regenerated in situ, and the spent regenerant in turn was decontaminated by a radium-selective mineral sorbent which fixed radium into the crystal lattice of the water-insoluble crystal. The pilot plant working upon this principle could process a very large water throughput and attained a very substantial volume concentration factor (about $2 \times 10^6$). However, the decontamination factor obtained never surpassed 20. Regeneration was a weak point and its improvement seems desirable [11].

Natural crushed barytes has been used to remove radium from effluent, but has not proved very satisfactory.

Mine drainage may still be a problem after the mine closes down. The composition of the effluent may change somewhat and generally will contain lower levels of contaminants and suspended solids.

The removal of sulphuric acid and metal ions from seepage from non-operational mines by using ion-exchange resins has been reported recently [12].

Seepage from waste rock piles, abandoned heap leaching piles and ore piles. This waste is similar to mine drainage and the above discussion also applies to this waste.

6.1.3. Airborne wastes

Besides containing radon (thoron) and its daughter products, exhaust ventilation is contaminated to some extent with ore dust, rock dust, and fumes from blasting and diesel engines.

As the level of contaminants in the mine air should be below the levels set for occupational exposure, no special provisions need normally be made for the discharge of this airborne effluent, as atmospheric dispersal rapidly dilutes the contaminants to levels below those appropriate for the general population.

However, these discharges may, under special conditions (inversions, mine conditions or proximity to large population centres) require some additional action or treatment to prevent an unacceptable situation developing. Thus it may be necessary, for example, to discharge the exhaust through a stack of sufficient height to restrict ground-level concentrations to acceptable values.

Although the control of dust from all operations is strictly the concern of occupational safety, the dust itself is a waste, and so requirements to reduce the release of dust are included in the Code. It must be borne in mind that occupational control does not necessarily provide for environmental control unless the dust is physically collected and prevented from contaminating the environment. Specific dust collection methods are discussed in Section 6.2.3.
6.2. Mill wastes

6.2.1. Solid wastes

Tailings. When the uranium is extracted from the ore, most of the 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 a waste disposal area.

As the major portion (at least 97%) of the $^{226}$Ra 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 [13]. It can be calculated, based on an estimated cumulative production of $1.5 \times 10^6$ tonnes U by 1990, that the total amount of $^{226}$Ra in tailings at that time will be of the order of 0.5 MCi. Although this is approximately the same amount that was originally naturally present in the massive orebody, it has now been transformed to finely ground sand and slimes which can be attractive for construction and other purposes. It is generally readily accessible, stored in large waste retention systems above ground level and subject to the vagaries of nature. Thus the potential impact of the contained radium has been significantly increased by the uranium extraction operation, and it is the function of waste management to ensure that all possible steps are taken to decrease the detrimental impact on man and his environment both now and in the future. It is interesting to note that the seas and oceans contain more than 1000 MCi of radium.

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 run-off, and the waste solutions. Sufficient radioactivity is in the tailings to create a weak field of gamma radiation in their immediate vicinity. Chemical pollutants, including various heavy metals, sulphates and sulphuric acid, may also be leached from the tailings and pollute surface or subsurface waters.

If the radium and other radionuclides could be removed from the tailings as a waste concentrate which could then be managed as a normal radioactive waste, then the tailings could be disposed of as normal mine tailings. Tests have shown that the radium can be removed [14], but the reagent costs and additional problems introduced by this process make it impractical at the present time.

At present there does not appear to be any generally applicable alternative to disposal of solid tailings in waste retention systems. These can and should be carefully sited, built to the best standards, operated in a careful manner and maintained at a high standard.

The site assessment for a waste retention system should include the drilling of a number of boreholes down to bedrock 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 the 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 seepage per year 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 content and compacted density. In-situ permeability measurements on the embankment during construction should also be performed.

Because it isolates the material from the external environment, backfilling of all or part of the tailings into worked-out portions of the mine appears to offer considerable promise if the whole operation is planned on this basis. However, there are considerable difficulties of an economic and practical nature. 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 daughter 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 agricultural 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 under adequate engineering control may increase the contaminant level in mine drainage but should not provide additional problems. Those backfilled into open cut mines may cause contamination of groundwater or surface water with radionuclides, heavy metals and other significant environmental pollutants.

In certain instances the discharge of tailings into isolated lakes that are not used for water supply purposes may be proposed. Such proposals should only be made after detailed investigation of the site, and may require the inclusion of provisions to reroute surface drainage and any through waters. Where underwater 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 have to be taken into account.

Tailings deposited in properly engineered, properly located waste retention systems do not present a significant hazard while the mill is operational and provided that they are properly managed. Even so it is possible for a dam wall 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 [15].

After the mill has been decommissioned, control, surveillance and maintenance of these waste retention systems present problems which will last into the future. Some of the problems are:

(a) 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. As an example, 20 earth embankments impounding phosphatic clay residues failed in the USA between 1942 and 1971 [16].

(b) Revegetation of tailings disposal sites is difficult to initiate and even more difficult to sustain. If a vegetative cover is not established, then wind and water erosion over the centuries could lead to widespread contamination of the surrounding area.

(c) 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 [17].

(d) Although normal atmospheric movement above the tailings usually ensures that hazardous concentrations of radon and daughters do not develop, this does not apply to any structures which may be built on waste retention systems. Thus it is essential to ensure that no habitable structures are built on them.

(e) Embankments which are built in valleys or natural drainage areas usually have a potential rainfall catchment area greater than the area of the tailings disposal site. 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 rain-water on to the tailings with the likelihood of erosion or possible failure of the embankment.

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

(g) 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:

\[
4\text{FeS}_2 + 2\text{H}_2\text{O} + 15\text{O}_2 \rightarrow 2\text{Fe}_3\text{(SO}_4\text{)}_3 + 2\text{H}_2\text{SO}_4
\]

The process of oxidation is both chemical and bacterial. The different forms of sulphide react differently but require water and oxygen as seen in the above equation. Light, temperature, acidity and bacteria will all influence the rate of reaction. Chemical oxidation is slow. More rapid oxidation by bacteria (\textit{Thiobacillus ferrooxidans}) occurs only below pH 3.5–4.0 with optimum conditions between pH 1.5 and pH 3.5 [18].

Confinement of tailings is usually accomplished by the construction of an embankment retention system. The design, construction and size of embankment retention systems will vary significantly from one milling location to another. The characteristics of these systems will depend on such diverse factors as the capacity of the mill, type of ore processed, amount of waste produced, type of milling process, topography of area, amount of land available, net evaporation rate, permeability of soil in the area, and the materials with which the embankments are constructed. The USA and Canada
have developed regulatory and design guides respectively for these embankments [5, 19] while a Code of Practice has been developed in South Africa [20].

An alternative approach to the construction of waste retention systems has been developed by Robinsky [21]. The primary aim of the new approach is to eliminate steep tailing slopes and the pond on top of the deposit. This is achieved by depositing the tailing in a cone-shaped hill — one of the most stable and erosion-resistant structural shapes found in nature. The operation requires that discharge of thickened tailing takes place from one permanent point within the impoundment area. On flat terrain this point would be located near the centre of the area ('Central Discharge'). As the tailing cone builds up the tailing line ramp and the central discharge point must be raised. This may be programmed for two- or three-year intervals. In valley terrain the discharge point would be permanently located on the valley wall at a point most distant from the overflow system of the pond. The conical shape of the deposit is achieved by thickening the tailing before discharge so that it settles out naturally at a slope of about 5 or 6%. Such slopes can be generally obtained at a solids-to-water ratio of 30 to 60% by weight. Initially, the solids-to-water ratio should be quite low so as to spread the tailing all the way to the design 'toe' of the conical deposit. As the tailing builds up, the solids-to-water ratio should be progressively increased, thus steepening the cone, but maintaining its 'toe' at the same point. If full thickening is allowed from the start, the tailing deposit will quickly build up at the point of discharge, forcing immediate raising of the tailing line ramp — an unnecessarily early expense.

The tailing, because of thickening, is deposited relatively homogeneously without segregation into 'coarse' and concentrated 'slimes' portions as in conventional tailing storage areas. For uranium ores such segregation is particularly undesirable as radium tends to accumulate in the finer 'slimes' portion of the deposit. With the proposed approach the fines are disseminated throughout the deposit, thus ensuring that the radium is uniformly dispersed.

The pond for settling out the very small quantity of slimes that has not settled with the thickened tailing is located near the perimeter, adjacent to the outside dyke. This dyke of natural materials is built to water storage dam specifications. Because the deposit of tailing is thickest at the centre and thinnest towards the perimeter of the cone, the required perimeter dykes are much lower than would be required for the traditional perimeter discharge system for the same storage capacity.

Decant towers and buried decant lines are not required. Since the pond level remains essentially unchanged throughout the life of the project, it is only necessary to supply a short overflow channel, spillway, or culverts at shallow depth. A conventional secondary pond for chemical treatment may be established at the outfall of the overflow system before recycling of the water.

This system is operating successfully at one mine (although not on uranium tailings) and has been adopted for several other mines. As the system appears to solve some of the problems of tailings disposal, it could be considered as an alternative during the planning stage.
As well as satisfying all the radiological safety, environmental and waste management aspects, the location selected for a waste retention system must also provide adequate safety for both workers and the surrounding population against a massive release of solids and/or liquids which may occur if the embankment fails. As there have been so many disasters of this kind in other mining operations, this aspect should be given careful consideration.

A basic decision on whether the waste retention system will be used to retain all the liquor which is discharged with the tailings and not reclaimed for reuse, or whether some of it will be released to the environment, should be made before design is commenced. In the former case, the excess liquor must either evaporate or seep away. Under these conditions it is generally considered that seepage should be kept to a minimum, and a tailings disposal site should therefore be selected which has a stable, impervious base. The embankment is also designed to incorporate an impervious seepage barrier. In this manner all the solid and liquid residues are retained in the embankment, and the release to the environment is minimal.

Where the evaporation rate or the area of the waste retention 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 syphons. The latter 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.

The procedures to be followed during the tailings disposal operation must be established at the time the waste retention system is designed, to ensure compatibility. These matters are addressed in Reference [5]. It is therefore essential for good coordination and cooperation to be established between the designers and the future operators, and for the operating procedures to be clearly described and made available to the operators. For this reason the manager must be fully aware of the operating procedures to be followed, and must take the responsibility of ensuring, by periodic inspection, that they are being followed.

Seepage (including embankment drainage) can be intercepted and collected by suitable drains, ditches or wells. Where all wastes are intended to be retained by the embankment, seepage should be returned to the pond. When discharge of liquid waste is practised the seepage can generally be treated and discharged with the decant liquor. For further details see Section 6.2.2.

**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. The two most common wastes which fall into this category are sludges containing a mixed precipitate of Ba(Ra)SO₄ produced during the treatment of decant liquor (see Section 5.2) and the filter cake containing radium and lead which is formed during the processing of monazite.
The Ba(Ra)SO₄ sludge is usually allowed to settle from the treated decant liquor in large settling ponds, where it is normally allowed to remain. This does not appear to be a satisfactory method of 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 waste retention system in such a manner that it is more or less uniformly dispersed in the tailings. Alternative procedures which may prove to be acceptable are solidification (either in situ or after collection) followed by burial at the site or in the tailings.

The radium/lead filter cake produced during monazite processing is normally packed into concrete lined drums and buried in a dedicated radioactive waste burial ground. This appears to be a suitable procedure.

An unusual and possibly unanticipated waste concentrate may be formed when sulphuric acid is produced from pyrites, recovered from uranium tailings, which contains some radium [22]. It has been found that the radium concentrates in scales in cyclones, in pipelines and in cooling, scrubbing and stripping towers. These scales may contain radium concentrations one or two orders of magnitude greater than in ore tailings. Careful disposal in the tailings appears to be satisfactory, as does burial in a dedicated radioactive waste burial ground.

**Scrap material and equipment.** Solid wastes from uranium and thorium milling operations may require handling as radioactive waste if they are significantly contaminated with radionuclides. Considerations similar to those developed in Section 4.1 also apply to this waste. The wastes may include scrapped ventilation ducting, clogged filters, filter cloths and scrapped equipment from the uranium or thorium recovery, drying and packing areas. It is normal practice to consign this material to the waste retention system in a position where it should be buried in a short time and finally covered to a depth of at least one metre, or bury it in a dedicated radioactive waste burial ground.

### 6.2.2. Liquid wastes

**Barren solution.** In the alkaline leaching process, the barren liquor is recovered and reused, and does not become a waste stream. The leached, washed tailings are transported to the waste retention system in a water slurry. The water slurry is slightly alkaline and may be contaminated with radioactive nuclides and chemicals, as indicated in Table 1, and may need treatment before disposal.

After the acid leaching process, however, the solution that is normally used to transport the tailings may contain greater concentrations of contaminants including sulphuric acid, heavy metals, nitrates, sulphates, organic solvents and amines (both from solvent extraction), chlorides and the radionuclides of which the most critical is ²²⁶Ra [23, 24], as well as other contaminants as shown in Table 1.

The most effective method for minimizing contamination of the environment by effluents from uranium milling operations is, of course, 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 new 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. The relative advantages of segregating waste streams for treatment should be assessed.

Where climatic conditions are favourable the discharge of effluents may be avoided by evaporation of excess water from the waste retention 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. Discharge of all or part of the treated or untreated effluent is generally regarded as less satisfactory but where the contaminants can be assimilated by receiving waters this method may be acceptable.

The safe disposal of radioactive wastes into rivers, lakes and estuaries is the subject of an IAEA Safety Series publication [25]. The necessity of controlling releases of radioactivity from the uranium and thorium industries is just as cogent as for any other source of radioactive waste.

The main process for the treatment of acidic mill effluents is neutralization with lime or a combination of limestone and lime [26]. During this step the following purification processes occur:

- \( \text{H}_2\text{SO}_4 \) is neutralized
- Some sulphate is precipitated
- Heavy metals are precipitated
- \(^{230}\text{Th}, ^{232}\text{Th}\), and \(^{210}\text{Pb}\) are removed to a low level
- \(^{226}\text{Ra}\) is removed to a great degree and it appears possible to reduce its presence to 100–200 pCi/l, or perhaps lower, by neutralization to pH 8
- Amine is removed by adsorption on precipitated solids.

In France, experience has shown that the effectiveness of radium removal by neutralization is noticeably affected by the neutralizing reagent used, lime or limestone. The use of limestone results in less effective removal of radium than when the pH is adjusted with lime. For this reason it is recommended that limestone be added to pH 2 only and that further neutralization to pH 8 or slightly higher be done with lime to provide optimum radium removal through the neutralization process alone.
Although barium treatment to precipitate radium is usually carried out on clarified solutions, it has been shown [27] that, after neutralization to pH 8 to 9, the addition of BaCl₂ solution to liquor decanted from the mill disposal tank, followed by the addition of an aqueous solution of a sodium salt of long-chain fatty acid such as oleic, palmitic or stearic at a rate of 10 mg per litre of effluent, leads to a flocculation of the sulphates 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 great reduction in specific activity. The oleate precipitate may be left under water where it is quite stable.

Starting with effluents containing between 100 and 1000 pCi radium per litre, the addition of barium chloride at 10 mg/l and of sodium oleate at 10 mg/l reduces the radium level to 2–5 pCi/l, a value which may be compared with levels of 0.1–10 pCi/l which occur naturally in rivers.

Decant solution. When effluent is to be discharged from the waste retention system, it is normal practice to neutralize the barren solution before it is discharged to the system. The decant solution can still contain from 100 to 1000 pCi/l ²²⁶Ra, sulphates and other contaminants.

The ²²⁶Ra is usually the contaminant which must be reduced before discharge. This can be done by coprecipitation with BaSO₄ by addition of BaCl₂ to the clarified liquor in the presence of excess sulphates at pH 8–9. 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. It would seem that BaCl₂ treatment when followed by adequate clarification may result in effluents containing as low as 3 pCi/l ²²⁶Ra. However, this cannot always be achieved in practice and the reasons for this have not been completely established at present. Adequate clarification is certainly important, and large settling basins must be provided.

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 simply because the operation has ceased, then problems will be encountered.

As operations continue, the precipitate will continue to accumulate and become a source of potential radium contamination which may be considerably more radioactive than the tailings solids. Depending of course 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. Before removal, sufficient quantities may have accumulated to require public access to the area to be limited.

Should the material not have to be removed to re-establish sufficient settling capacity in the settling basin, it will continue to be a potential hazard in that the precipitate was formed from solution containing certain ionic species at various concentrations. If for any reason, such as those indicated above, there is a change in the
supernatant liquid, then the precipitate can progressively redissolve and result in effluents containing non-acceptable levels of radium. As an example, when operations cease, the material, unless it is treated in some way, will probably be subjected to contact with rain or surface water of low sulphate content which it is known will cause re-solution.

In addition, in unusual conditions such as particularly heavy rain or if an embankment fails, the sludge can be washed downstream into public receiving waters. Should this occur it will present a radiological hazard both as regards ingestion of particulate matter and as a source of radium for dissolution by the receiving water.

**Tailings seepage.** Tailings seepage changes in character with time as the system 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 (say 1000 pCi/l), 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 levels 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 very acid seepage which may contain high levels of heavy metals, manganese, sulphate, etc., although the radium content may be quite low (say 20 pCi/l).

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. Because of the lack of power, supervision and maintenance, this is rarely possible after operations cease. If conditions are suitable, the seepage can be collected in a basin downstream of the embankment, where it can then evaporate, leaving a salt deposit in the basin.

When decant solution is discharged from the embankment, the seepage can be combined with it and treated in the same way. As the decant solution is normally alkaline, and of much greater volume than the seepage, the final effluent will normally be neutral or alkaline and thus contain only low levels of most heavy metals. When operations cease, however, and there is no decant solution to neutralize it, the seepage can cause problems by changing the pH of the receiving waters and by adding significant quantities of heavy metals to them.

Simple neutralizing plants, powered by the flow of seepage and requiring a minimum of attention, can be constructed, but it is difficult to ensure that they provide the right degree of treatment, and that they can be kept operating well into the future. Where the effects from seepage are potentially serious, it appears that some form of continuous control is required. How this is achieved is a matter for the competent authority to decide.

**Thorium milling effluent.** The liquid effluents from thorium milling consist of plant and floor washings, filtrates and filter cake washings. They may contain some particulate material and salts, acids, thorium, uranium and rare earths in solution. In
India these wastes are led through a set of settling tanks before discharge to a river having a high flow rate. Effluent monitoring is done to ensure that the discharges are well below the allowable limits. To further reduce the radionuclides in the liquid effluents, additional settling and filtration facilities and a radium removal step are being investigated.

Assessment of the environmental impact associated with the disposal of monazite processing wastes is made difficult by the varying degree of separation achieved for thorium and daughter products, the concentration of the various daughter products, and the build-up of activity after processing [28].

6.2.3. Airborne wastes

Dry ore dusts are normally generated during crushing and dry screening operations. They are removed by dust extraction units incorporating hoods, ducts, fans, cyclones and wet scrubbing devices to capture particles and return them to the process stream. Roasting of ores requires dust recovery equipment incorporating dry cyclones, wet scrubbing and possibly electrostatic precipitation. 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 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.

Radon is released 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. However, the radon released in effluents from milling operations does not appear to pose a significant hazard.

The release of radon from waste retention systems is mentioned in Section 6.2.1. The radiation dose caused by radon is a function of the state of equilibrium between radon and its daughters at the time of exposure, and therefore it is not enough simply to know the radon-222 concentration alone. Long-term exposure occurs because the tailings from the mill contain long-lived $^{226}$Ra, the parent of radon, so that radon will be continually produced and will emanate from the pile indefinitely. A value of 1 pCi/l above background, which may range from 0.1 to 1.0 pCi/l in the free atmosphere and
from 1 to 10 pCi/l in granite dwellings, has been used as the recommended limit for continuous exposure to individuals in the general population [29].

Wind-borne particulate material originating from the surface of the waste retention system may also be of some significance. These releases present a potential health hazard which requires evaluation in each particular case. It appears that radon releases, which are the most difficult to control, are of most significance, but that radioactive particulate releases may sometimes also be significant [30].

Radon emanation and the release of radioactive particulates from a given amount of tailings are reduced when:
- the area of tailings exposed is decreased;
- the tailings are under water, ice or snow;
- the tailings are covered with a thick layer of earth or with an impermeable membrane.

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

In spite of some uncertainty regarding the actual health effect of radon and particulates released from tailings, it appears prudent to utilize all the above mechanisms as far as practicable to limit the potential future detriment.

6.3. 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 leach liquor, which is then chemically adjusted and recirculated through the leaching field.

Because the leach liquor may pick up materials other than uranium, a portion or all of it may have to be bled off or treated to remove impurities or suspended solids. Thus some liquid wastes, sludges and filter backwash may be produced as waste. In one operation [31], chemical wastes from the plant are disposed of in reservoirs with an impermeable lining, which are sized so that evaporation balances inflow.

The sources of air emissions in the process are limited to open tanks containing leaching solutions which may release radon, and dust from the yellowcake drier. Both of these can be adequately controlled, the former by ventilating the tanks and the latter by an appropriate filter or scrubber.

Apart from the sludges mentioned above, there are no solid wastes, since the radium-contaminated residual orebody remains underground.

Additional liquid wastes may be produced when the leaching field is closed down. If the site must be left in a chemical and hydrological condition similar to that obtaining 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 method chosen for the operation mentioned above is to pump contaminated solutions out of the leached zone via a 1370-m-deep disposal well into a saline water aquifer.

7. DECOMMISSIONING REQUIREMENTS

It has been normal industrial practice that most mines and mills, at the end of their useful lives, have been decommissioned to the extent that all potentially useful plant, equipment and buildings have been sold, the mine has been made safe and closed and the remaining structures have been made safe. The proceeds of the sale of materials have defrayed part or all of the cost of decommissioning.

Additional actions are now being required by environmental authorities such as the restoration of the original land surfaces for open cut mines, the stabilization, shaping and revegetation of waste retention systems and waste rock piles, and the removal of all structures from the area.

These requirements exist for uranium and thorium mines and mills, but additional ones also have to be met because of the presence of radionuclides in the mine, in waste rock and heap leach piles, in and on plant, equipment and buildings and in the waste retention system.

Very few countries have any experience in the decommissioning of uranium mine and mill sites. The United States does have certain regulations concerning the clean-up levels necessary to decontaminate abandoned buildings and the surrounding area. These regulations also hold at abandoned uranium ore buying stations. The procedures are necessary especially in areas where the mill site may be utilized after the mill has shut down. In the western United States, where over twenty uranium mills have been closed down, the local residents are often interested in utilizing the remaining buildings. Extensive decontamination procedures have been necessary to reduce levels of contamination at the sites of former milling activities, uranium tailings and former ore stockpiles.

As some uranium waste retention systems have not been properly stabilized, criteria are necessary for decontaminating the area surrounding the abandoned system before stabilization can be started. Decontamination criteria are now being developed for a USA study on the potential public health problem of non-operating uranium waste retention systems.

The approach to this problem that has been adopted in the Code is to recognize that some places may always be contaminated and that it is impractical to decontaminate them since they will naturally recontaminate themselves. These places need to be permanently dedicated as areas affected by waste residues.

7.1. Mines

It is most unlikely that a worked-out uranium or thorium mine could ever be said to be free of radioactivity. However, it appears possible to decontaminate most of the
area and buildings so that they can be released for unrestricted use, while the remaining activity is confined to selected areas which may require some permanent restrictions on future use. These areas are now discussed:

Underground mines will almost inevitably contain some unextracted ore and may also contain large quantities of mineralized rock of sub-economic grade and tailings, all of which will release radon and may also contaminate mine waters as and when the mine fills with water. Circumstances will vary the approach to be adopted in each case, but generally all possible entry points to the mine should be sealed to retain the radon and prevent unauthorized entry. Where all the mine water cannot be safely retained in the mine, suitable drainage provisions should be made to release the excess water. These drainage points should be made through a seal so that release of radon and unauthorized access to the mine interior is impossible.

Open-cut mines are unlikely to contain as much unextracted ore as underground mines, but may, nevertheless, contain other contaminants such as sulphides, heavy metals, etc. The reclamation and restoration of one such mine has been planned [32].

Waste rock and heap leaching piles may contain some uranium, radium, sulphides and heavy metals which may require that they cannot be released for unrestricted access. They must be made physically stable by lowering their height, flattening their side slopes or taking such other action as may be necessary. In addition their aesthetic impact should be reduced if possible by suitable shaping, and they should be revegetated to further improve their stability, to reduce dust hazards and to improve their appearance. After completion of these operations and due consideration of any hazard which may be posed by the piles, it may be possible to return the area to some appropriate land use.

All possible efforts should be taken, from initial planning through the operating phase to the actions taken during decommissioning, to end up with sites which do not release drainage waters that require treatment. Continuing treatment of these wastes after mining and milling operations cease is difficult and costly to achieve. Prevention is better than cure. Treatment methods are discussed in Section 6.1.2.

7.2. Mills

The same considerations apply as for mines, but the only areas which will have to be left in a condition not suitable for unrestricted release after decommissioning are the waste retention systems and heap leach sites, which, as already discussed, contain radium and other daughter products as well as other potential contaminants such as active sulphides and heavy metals.

The decommissioning of mill sites may require the removal of contaminated ground, floors and building foundations. These wastes should be deposited in the waste retention system before permanent stabilization is begun.

Stabilization of these sites is required to prevent wind and water erosion, to improve long-term stability, to reduce the maintenance problem and to improve their appearance.
Revegetation appears to be the method of stabilization which accomplishes most of these objectives, but it is not universally applicable to all sites because of climatic, geographical or other limitations [33–35]. It is a relatively new development and not a great deal of practical knowledge has evolved during the few years it has been tried.

Alternative procedures which may be applicable in some cases are to cover the wastes with crushed rock (possibly waste rock from the mine) to a sufficient depth, or to stabilize the surface using chemical admixtures [36], cement or bitumen. These latter procedures, however, do not promise to be very long lasting. They may be useful as interim measures before revegetation or to assist in revegetation by preventing wind erosion.

Before stabilization can begin, the final form of the waste retention system must be decided. Typical questions which have to 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 domed 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 so 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 embankment, which is of paramount concern in providing safety in all circumstances.

Because of the long half-life of the contaminants, it is essential that, where warranted, the sites are marked, identified and isolated in such a manner that future generations will be aware of the possible risks if the sites are not suitable for unrestricted use.

It is considered that fences and conventional notices are of limited value in this regard, although they are useful in the short term.

Massive concrete, stone or metal markers carrying information on engraved metal plates protected from the weather may be more useful.

The most permanent method, however, appears to be the endorsement of the appropriate information on local and national land survey plans and title deeds, and the placing of covenants on the use of the land. Although this ensures that the information should always be available it does not ensure that individuals will be aware of the restrictions.

Thus it appears necessary for some permanent national organization to be required to accept responsibility for ensuring that the restrictions on these sites are not violated.

7.3. Decontamination procedures and surface contamination levels

The decontamination of plant, equipment and buildings has been extensively reported [37, 38] and will not be discussed further. Large 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 radioactive contamination survey instruments. The contaminated material so removed may be treated in the mill for recovery of contained uranium or thorium. Alternatively it may be disposed of to waste rock piles, waste retention systems or to the mine as approved by the competent authority.

The decontamination procedures should be continued until the residual contamination of the surface is reduced to an acceptable level. Unfortunately for surface contamination there are no internationally agreed permissible levels. Acceptable surface contamination levels may be influenced by:

(a) The nature and quantity of the contaminating radionuclide;
(b) The nature of the contaminated surface, e.g. its structure and condition;
(c) Environmental factors, e.g. degree of occupancy, ventilation, climate, use of area.

The results of measurements of surface contamination cannot be related quantitatively to the level of the related hazard, because most monitoring instruments available are merely qualitative — they cannot identify the radionuclide, measure the activity actually on the surface, or otherwise determine the extent of the hazard to persons.

Some values of maximum permissible levels for surface contamination which have been used in different countries are given in References [39, 40]. These mainly relate to working surfaces, containment surfaces, skin and clothing, and may not be particularly appropriate for decommissioned sites. In particular, the level of contamination on and in soil which may be acceptable is extremely difficult to define. It is suggested that levels which represent some low multiple of the natural background in the general area (e.g. 2 to 5 times the background) should provide adequate safety and be readily attainable. In general, the 'as low as reasonably achievable' concept should apply.

After due consideration of the potential hazard presented by the contamination, appropriate levels may be approved for specific items or areas.

8. FINANCIAL ARRANGEMENTS FOR MAINTENANCE AND MONITORING OF MINES, TAILINGS AND HEAP LEACH AREAS AFTER DECOMMISSIONING

It is apparent that some costs will be incurred after decommissioning to monitor and maintain the above sites in a satisfactory condition. These costs can include such items as inspection and maintenance of fences, notices, diversionary dams and ditches, the mine drainage system, the tailings embankment, vegetative cover, etc.

Apart from the bonding or escrow accounts mentioned in the Code, it is considered that this work could be financed from the interest earned by a fund accumulated during the mining and/or milling operation by collecting an appropriate contribution for each
9. PERIODIC INSPECTIONS OF WASTES AND THE ENVIRONMENT

To ensure that the wastes are under control, it is clearly necessary that they be inspected from time to time. Where the environment may be affected, appropriate samples must be taken and examined to measure the effect. This is in addition to samples of effluent which may be taken to comply with discharge limitations.

In the Code the manager is made responsible for ensuring that such inspections are carried out during operations and until the site is decommissioned, while the owner of the site is made responsible after that period. This has been done to ensure that there is a clear and unambiguous responsibility at all times.

Recommended procedures for inspection of tailings embankments are given in Reference [10]. Settling ponds, lagoons and effluent discharge arrangements should be inspected on a similar basis.

Environmental samples, selected to detect damage to the environment, may include such materials as stream and aquifer water, fish, stream sediments, and agricultural products grown using irrigation water contaminated with effluent. These should be collected and analysed initially at three-monthly intervals. Results may indicate that the frequency can be relaxed, but some relevant sampling should be carried out at least once a year.

10. TRANSFER OF OWNERSHIP

Because of the difficulties involved in ensuring that either the manager or the operator remains capable of meeting the future obligations for monitoring and maintenance of any land affected by mining and milling wastes, it is considered that these obligations should 'run with the land', with the result that upon a change in the ownership of the land, the new owner would incur the obligations.

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