COMMONWEALTH DEPARTMENT OF HEALTH

# Australian Radiation Laboratory

## Radiation Protection in the Mining and Milling of Radioactive Ores.

## VOLUME 2

Lecture Notes from a 2 week course conducted
at the Australian Radiation Laboratory,
February 2-13, 1981.

Edited by John F. Boas

Vol 2

Pages 324 - 350

ARL/TR 043
ISSN-1400
JANUARY 1982

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# Chapter 15. Radioactive Waste Management with Special Reference to Mining and Milling of Radioactive Ores

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Abstract. The principles and objectives of general radioactive waste management are outlined. The nature and composition of wastes from mining and milling or uranium and thorium ores are described; alternative management procedures, engineering technologies and some promising new developments for disposal of mill tailings are discussed.

International studies on the disposal of uranium mill tailings are described with particular reference to long term performance objectives. Some National proposals of criteria for tailings disposal practices are discussed.

Experience of mining and milling uranium ores in Australia is reviewed briefly and problems arising from some former practices noted. The status of development of major Australian uranium resources is reviewed together with relevant legislative developments and environmental requirements.

## INTRODUCTION

One of the consequences of the commercial application of radioactivity is the production of a wide range of radioactive wastes which are potentially injurious to health. These wastes may contain radioactive materials occurring in nature - as in the case of mining and milling of radioactive ores, or alternatively may be produced by nuclear fission reactions in nuclear power generation, or in the manufacture and use of radioisotopes for medical and industrial purposes.

The majority of wastes containing natural radioactivity are derived from sources of uranium and thorium, e.g. in the mining and treatment of uranium ores or in the mining and processing of beach sands containing monazite for recovery of thorium and/or rare earths. Because of the ubiquitous distribution of traces of uranium and thorium in the earth's crust, wastes containing small quantities of naturally occurring radioactivity can also be produced from many industrial operations as diverse as the mining and use of rock phosphates for fertilizer production and of coal for energy.

This lecture discusses the general principles and objectives of radioactive waste management, with specific reference to wastes from the mining and processing of uranium and thorium ores.

## PRINCIPLES AND OBJECTIVES OF RADIOACTIVE WASTE MANAGEMENT

### Waste Form Characterization

Radioactive wastes are produced in all physical forms, that is, as gases, liquids and solids and have an extremely wide range of activities ranging from near background levels to several tens of hundreds of thousands of terabecquerels (TBq) per cubic metre of waste - a range of concentration in excess of $10^{15}$. The radioactivity is continually reduced as the radioactive nuclei decay into stable isotopes, the rate of reduction being governed by the half-lives of the particular isotopes contained in the waste. Wastes also have four other features which must be considered in their characterization, viz. toxicity, mobility, radioactive half life, and type of radioactive emission (α-particle, β-particle, γ-ray or neutron). These characteristics govern the choice of management procedures to be adopted.

## Scope of Waste Management

Waste management includes all activities, administrative and operational, which are involved in the handling, treatment, conditioning, transportation, storage and disposal of waste. The distinction between storage and disposal may be noted: storage is the emplacement of waste in a facility with the intent that it will be retrieved at a later time. By contrast, disposal is defined as a method of management in which there is no intention to retrieve and in which the integrity of the method does not rely on the continued provision of human intervention whether this be for monitoring, treatment, or restriction of access.

## Principles of Disposal of Radioactive Wastes

Three basic principles are employed in radioactive waste disposal. They are:

(a) Dilution and dispersion of short-lived or very dilute radioactive wastes. The radioactivity may be reduced to acceptable levels by dilution in the environment. Quantitative physical, chemical and biological data and knowledge of dispersion phenomena and reconcentration factors at the specific disposal site are essential.

(b) Concentration and containment of long-lived radioactivity. These wastes are confined in specially engineered structures; thus uranium mill tailings are disposed of into above ground or sub-surface retention systems, and it is intended to dispose of solidified highly radioactive wastes from spent reactor fuel by deep geologic burial.

(c) Delay and decay storage of very short-lived radioactive wastes to permit their decay into non-radioactive species.

These principles are applied separately or in combination, depending on the nature and concentration of the radioactivity in the wastes.

This radioactivity may present only a small portion of the potential hazard of the waste, e.g. the chemical toxicity of the element uranium is greater than its radiotoxicity, and in the case of uranium mining, non-radioactive toxic elements present in the ore may have predominant potential for adverse environmental effects. Treatment and disposal practices for radioactive wastes may therefore include the safe management of non-radioactive but highly toxic chemical wastes.

## Objectives in Disposal of Radioactive Wastes

The basic objective in the disposal of radioactive wastes is the protection of man and the environment from unacceptable harm. In effect this means achieving a sufficient degree of isolation or dilution of the wastes so that any return of radionuclides to the biosphere is at a rate and/or concentration sufficiently low as not to present an unacceptable biological hazard. A further objective is to achieve the degree of isolation required for long lived wastes without reliance on long term surveillance.

## Disposal Options for Radioactive Wastes

The options available are dependent on the characteristics of the wastes (Section 2.1) and may be summarised as follows:

Solids: Above ground retention systems; shallow surface burial; deep geologic burial; ocean dumping.
Liquids: Discharge to waterways, estuaries and coastal waters; evaporation.
Gases and Airborne Particulates: Atmospheric discharge; retention.

Owing to the extremely long half-lives of some radionuclides, disposed of by isolation, it is necessary to give special considerations to the long-term behaviour of the containment system. The important activities related to the disposal are the selection of the appropriate disposal location and engineered barriers, and the isolation of the waste from the biosphere. A safety analysis of the overall system must be performed to show that effective isolation will result from the planned disposal, and the safety model must be validated by site-specific measurements. Disposal operations involving dispersion of the wastes to the biosphere are monitored to ensure that the resultant dose to man is kept as low as practicable and within the recommended limits set by the International Commission on Radiological Protection (NEA 1977).

## National Attitudes to Radioactive Waste Management

All major countries having a nuclear program, whether it be nuclear power and/or a radioisotopes industry, have legislation in place to regulate the management and disposal of these radioactive wastes. National standards for protection of human health and the environment differ, but are usually derived from the comprehensive system of dose limitation recommended by the International Commission on Radiological Protection (ICRP 1977), the main features of which are:-

(a) no practice shall be adopted unless its introduction produces a positive net benefit;
(b) all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account;
(c) the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission.

In Australia, the National Health and Medical Research Council has endorsed the use of the ICRP System of dose limitation without modification (NH and MRC 1980). The most recent statement on radiological protection principles in the UK (UKDOE 1979) corresponds closely with the main recommendations of the ICRP.

In the US, judgements of what is as low as reasonably achievable have been taken into account in adoption of standards relating to particular classes of installations. The US National Regulatory Commission (USNRC) has issued some numerical guidelines to limit the environmental impact of the nuclear fuel cycle. These guidelines have been based on the cost-effectiveness of controls limiting discharges of radioactivity from specific classes of operations (NEA 1977).

Several countries do not adopt a policy of "complete isolation over the hazardous lifetime". Canada, France, Germany and the U.K. dispose of low level waste in some or all of the following ways: burial at shallow depths, discharge to the sea and dumping in the North Atlantic Ocean. Japan has announced its intention to conduct tests to investigate the safety of dumping radioactive wastes at a depth of 6000 metres in the Pacific Ocean.

Ocean dumping typifies the differences in national attitudes towards waste isolation versus dispersion. Ocean dumping of solid low and medium level radioactive waste has been practised from 1946 until the mid-1960s on a national basis, particularly by the United States in the earlier part of this period and by the United Kingdom. Since 1967 it has been practised by a number of European countries under international arrangements operated by the Nuclear Energy Agency (NEA) of OECD. Since 1975, dumping has been carried out under the International (London) Convention on the advice of the International Atomic Energy Agency (IAEA). The practice is supported by Belgium, Japan, Netherlands, Switzerland and the UK, opposed by Canada, Ireland, Italy, Portugal, Spain and the US, while France and the F.R.G. have adopted a neutral stance.

These divergent attitudes towards ocean dumping are caused by a variety of factors including political considerations, social perceptions, and differing technical views on the validity of oceanographic modelling exercises.

The implementation of uniform waste management policies throughout the world is proving to be difficult. While technology exists for appropriate disposal methods, and there is no evidence to indicate that the ICRP's recommended system of dose limitation has failed to provide an adequate level of safety, there is a lack of public acceptance of some of these policies.

## COMPOSITION AND MANAGEMENT OF WASTES FROM MINING AND PROCESSING RADIOACTIVE ORES

### Uranium Ores

The radioactive decay series for uranium-238 is shown in Table 1. The radiologically significant isotopes in the series are the long-lived alpha emitters $^{238}$U, $^{230}$Th and $^{226}$Rn and its short-lived daughter products; and $^{210}$Pb and $^{210}$Po, the long-lived daughter products of $^{222}$Rn. About 10 G Bq (0.3 Ci) of each isotope is associated with ore containing 1 tonne of uranium if secular equilibrium exists.

Up to $99^{o}/o$ of $^{226}$Ra and of $^{230}$Th may be rejected as insoluble waste at the leaching stage; $^{230}$Th may be removed in wastes from leaching and purification; $^{210}$Pb, $^{210}$Po and $^{214}$Po may appear in wastes or with the uranium concentrate product, depending on the treatment processes.

### Uranium mining wastes and effluents

Wastes produced during mining of uranium ores are mainly site-specific; they depend in quantity and nature on the composition of the ore body and its host rock and the method of mining employed.

Solid waste produced in open-cut mining operations is the earth overburden above the orebody and the barren rock in which the ore is dispersed. Underground mining produces less rock; solution mining, where the ore is leached in situ and the solution extracted for treatment does not produce comparable mining waste.

Initially, waste rock from excavation, if free from potential contaminants such as pyritic material, may be used for construction of earthworks, foundations and roads. Excess rock is transported to a dump near the mine.

## TABLE 1

## URANIUM RADIOACTIVE DECAY SERIES

(Minor branches not shown)

| Radioelement | Isotope | Radiation | Half Life | Remarks |
|---|---|---|---|---|
| Uranium I | $^{238}_{92}U$ | α | 4.5 x $10^{9}$yr | |
| ↓ | | | | |
| Uranium $X_1$ | $^{234}_{90}Th$ | β, γ | 24.1d | β rays in uranium metal and ore come from these |
| ↓ | | | | |
| Uranium $X_2$ | $^{234}_{91}Pa$ | β, γ | 1.17 min | |
| ↓ | | | | |
| Uranium II | $^{234}_{92}U$ | α, γ | 2.5 x $10^{5}$yr | |
| ↓ | | | | |
| Ionium | $^{230}_{90}Th$ | α, γ | 80,000 yr | |
| ↓ | | | | |
| Radium | $^{226}_{88}Ra$ | α, γ | 1620 yr | |
| ↓ | | | | |
| Radon | $^{222}_{86}Rn^{*}$ | α | 3.83 d | gas |
| ↓ | | | | |
| Radium A | $^{218}_{84}Po^{*}$ | α | 3.05 min | collects on dust in mine |
| ↓ | | | | |
| Radium B | $^{214}_{82}Pb$ | β, γ | 26.8 min | β and γ rays in mine come from these |
| ↓ | | | | |
| Radium C | $^{214}_{83}Bi$ | β, γ | 19.7 min | |
| ↓ | | | | |
| Radium $C^1$ | $^{214}_{84}Po^{*}$ | α | 1.64 x $10^{-4}$s | collects on dust in mine |
| ↓ | | | | |
| Radium D | $^{210}_{82}Pb$ | β, γ | 22 yr | |
| ↓ | | | | |
| Radium E | $^{210}_{83}Bi$ | β | 5 d | |
| ↓ | | | | |
| Radium F | $^{210}_{84}Po^{*}$ | α | 140 d | |
| ↓ | | | | |
| Radium G(stable) | $^{206}_{82}Pb$ | - | - | |

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*Constitutes the α hazard in mining, etc.

Other solid waste material, separately stockpiled, consists of rock which bears traces of uranium below the economic cutoff grade.

Liquid effluent from uranium mining consists of surface water runoff from the waste rock and ore stockpiles, water seepage through the waste rock and ore stockpiles, and water seepage into the mine. This effluent may contain suspended solids and dissolved minerals, including uranium and its decay products, and will continue to be produced after the mining operation has ceased.

Airborne effluents from uranium mining consist of dusts containing uranium and its decay products, radon-222 released to the atmosphere during exposure and breakup of the orebody, and the combustion products of petroleum fuels used by the mining equipment. Radon emanation from the mine and solid wastes will, in most cases, continue after the mining operation has ceased.

### Uranium milling wastes from excavated ores

There are essentially two alternative methods of uranium ore milling; uranium is leached from the finely ground ore either by sulphuric acid or by sodium carbonate, the choice being determined mainly by the acidity or alkalinity of the host rock. Figs. 1 and 2 show, respectively, typical acid and alkaline leach processes and waste streams.

The acid leach process is suitable for the majority of ores, while carbonate leaching is applicable to some uranium deposits in Western Australia, Canada and the US. These processes extract about 90-95$^{o}$/o of the uranium content of the ore.

For ores mined by open cut or underground methods, the tailings slurry is the major chemical and radiological waste from the milling process. This stream is a slurry of leached solid ore and waste solutions from the grinding, leaching, uranium purification, precipitation and washing circuits of the mill. The solution from an acid leach process contains predominantly sulphate ions with quantities of soluble metal ions and traces of organic solvents. The sodium removal step in a carbonate leach process also produces a sulphate waste solution. The neutralised solid tailings consist of unleached rock and precipitated mineral hydroxides. With little of the parent uranium remaining, the short-lived daughters Th-234 and Pa-234 are lost by decay from the mill wastes. The remaining 70 per cent of the activity originally present in the ore remains in the waste stream (UNSCEAR 1977). Tailings from an acid leach process contain about 95$^{o}$/o of the thorium and up to 99.9$^{o}$/o of the radium originally present in the ore; carbonate leach tailings contain about 98$^{o}$/o of the original radium (Tsivoglou and O'Connell 1963).

The tailings slurry is pumped into a system designed to retain all solids. Management of liquid wastes is very dependent on climate and ranges from treatment prior to discharge to almost total retention.

Radioactive airborne effluents from milling include dusts and radon gas released into the air from ore stockpiles, the crushing, grinding and leaching operations and from the tailings retention system. Releases of dusts produced during crushing and grinding of ore and calcining and packaging of yellowcake are reduced by ventilation extract scrubbers. Tailings piles are a continuing source of radon gas and radioactive dust after milling operations have ceased, the extent of emission being dependent on the rehabilitation measures adopted for the piles.

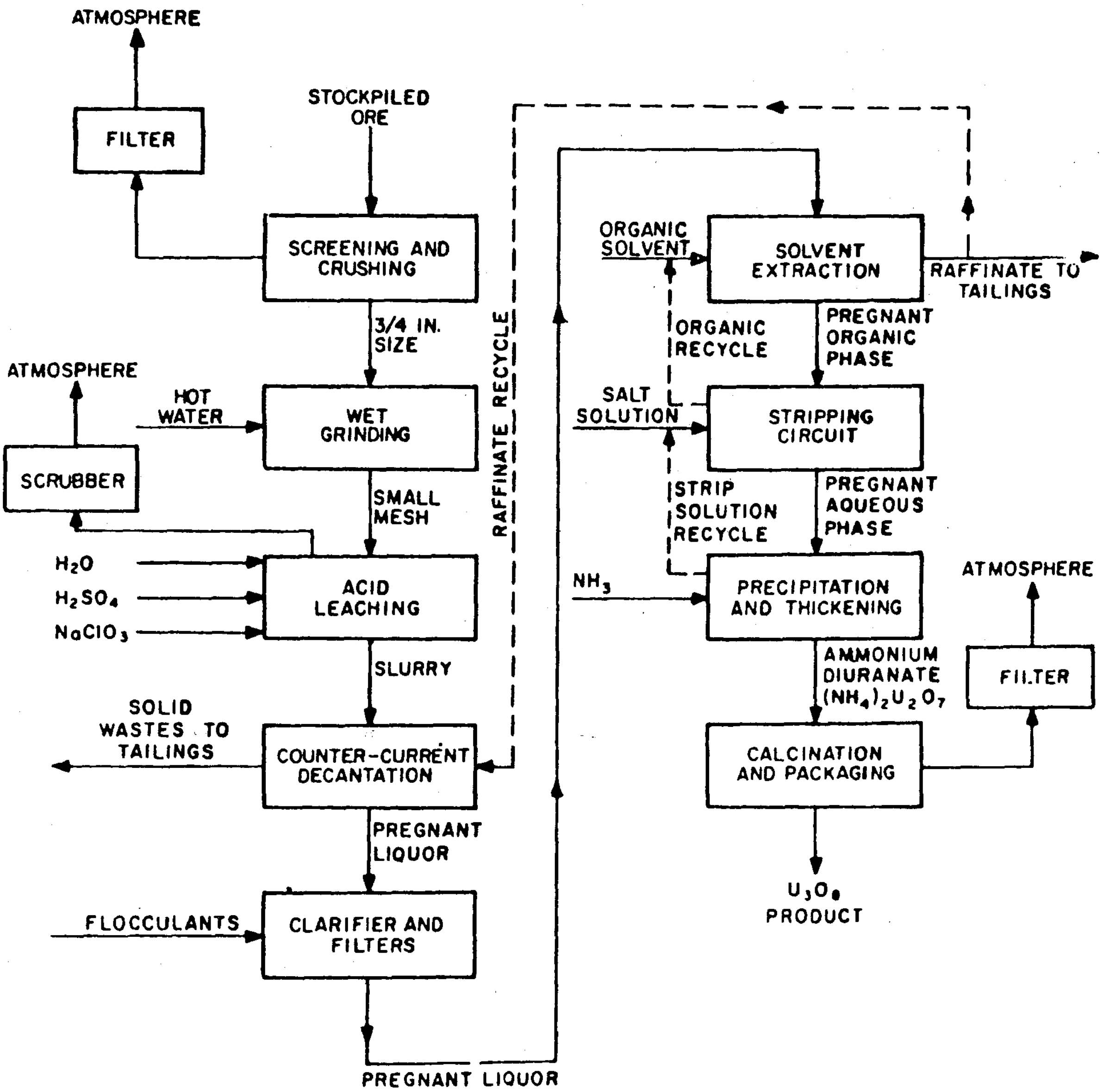


Figure 1. Simplified Flow Diagram for Uranium Milling Acid Leach Process

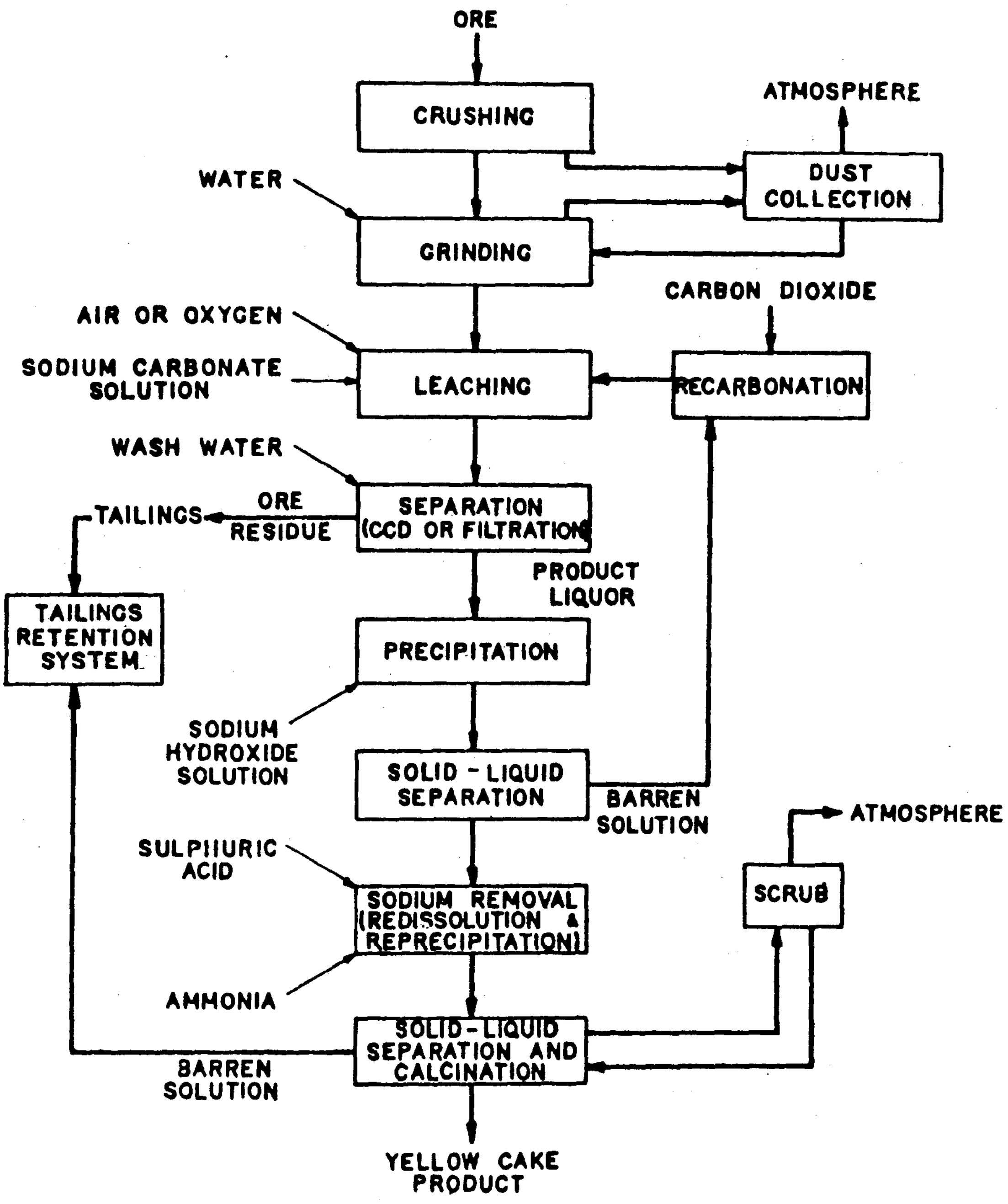


Figure 2. Uranium Mill - Carbonate Leach Process Simplified Block Flow Diagram.

Airborne chemical contaminants released to the environment include combustion products (oxides of carbon, nitrogen and sulphur) from the process steam boilers, sulphuric acid fumes in small concentrations from the leach tanks, oxides of sulphur and sulphuric acid fumes from the sulphuric acid plant, and traces of vaporised organic reagents from the solvent extraction ventilation system.

## Process wastes from solution mining of uranium

Extraction of uranium from solution mining operations involves chemical treatment of leach liquor circulated through and removed from the ore body. Residues consist of liquid wastes and sludges, produced as evaporator concentrates of small volume, and containing chemical and mineralogical residues. These wastes contain less radioactivity per tonne of uranium extracted than from milling of ores mined by mechanical methods, owing to the selective leaching processes employed which leave the majority of the uranium daughters other than Rn-222 and Th-230 in the residual underground orebody. The liquid and sludge concentrates are generally stored in shallow reservoirs with low permeability liners to restrict seepage (IAEA 1976).

Radioactive airborne emissions from treatment of solution mining extracts consist of radon gas released from open tanks containing leach solutions, and dusts from yellowcake calcination.

## Thorium Ores

The radioactive decay series for thorium-232 is shown in Table 2. The radiologically significant isotopes in the series are the long lived alpha-emitter $^{232}Th$; short lived alpha-emitters $^{228}Th$ and $^{224}Ra$; and $^{220}Rn$ and its short lived daughter products. About 4 G Bq (0.1 Ci) of each isotope is associated with ore containing 1 tonne of thorium in secular equilibrium.

## Thorium mining wastes

Some thorium ore has been extracted by underground mining operations that are comparable to those used for uranium mining, except that the ore is generally of a higher grade. The wastes arising from these thorium operations are of the same types as those from uranium mining.

Thorium is usually mined by dredging or excavating beach sands containing monazite, a compound of typical composition 9.5°/o $ThO_2$, 28°/o $P_2O_5$, 60°/o rare earth oxides and 0.3-0.4°/o $U_3O_8$ and is often associated with the mining and recovery of rutile (titanium dioxide ore), zircon (zirconium silicate) and ilmenite (titanium iron ore) (IAEA 1976).

## Thorium milling wastes

Figure 3 shows a typical treatment process for recovery of thorium from monazite. Operations include grinding, acid leaching and solvent extraction (ERDA 1976). An alternative treatment process involves digestion of ground ore with alkali, and controlled leaching with hydrochloric acid (IAEA 1976).

Airborne dusts and thoron gas are liberated during the grinding stage. Some other operations, such as the filtration and drying of thorium concentrates and the evaporation of the rare earth extracts may 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. Solid wastes consist of filter cake or sludge from purification steps and scrapped filter cloth and equipment. Waste slurries from thorium milling are discharged to solids retention systems.

## TABLE 2

## THORIUM RADIOACTIVE DECAY SERIES

| Radioelement | Isotope | Radiation | Half Life | Remarks |
|---|---|---|---|---|
| Thorium | $^{232}_{90}$Th | α | 1.4 x $10^{10}$ yr | |
| Mesothorium I | $^{228}_{88}$Ra | β | 5.8 yr | Source of β and γ rays from thorium metal and ore |
| Mesothorium II | $^{228}_{89}$Ac | β, γ | 6.1 hr | |
| Radiothorium | $^{228}_{90}$Th | α, γ | 1.9 yr | |
| Thorium X | $^{224}_{88}$Ra | α, γ | 3.64 d | |
| Thoron | $^{220}_{86}$Rn* | α | 55 s | gas |
| Thorium A | $^{216}_{84}$Po* | α | 0.15 s | collects on dust in mine |
| Thorium B | $^{212}_{82}$Pb | β, γ | 10.64 hr | β and γ rays in mine come from these |
| Thorium C | $^{212}_{83}$Bi* | α, β, γ | 60.6 min | |
| Thorium $C^1$ | $^{212}_{84}$Po* | α | 304 ns | collects on dust in mine |
| Thorium $C^{11}$ | $^{208}_{83}$Tl | β, γ | 3.1 min | |
| Thorium D (stable) | $^{208}_{82}$Pb | - | - | |

*Constitutes the α hazard in mining, etc.

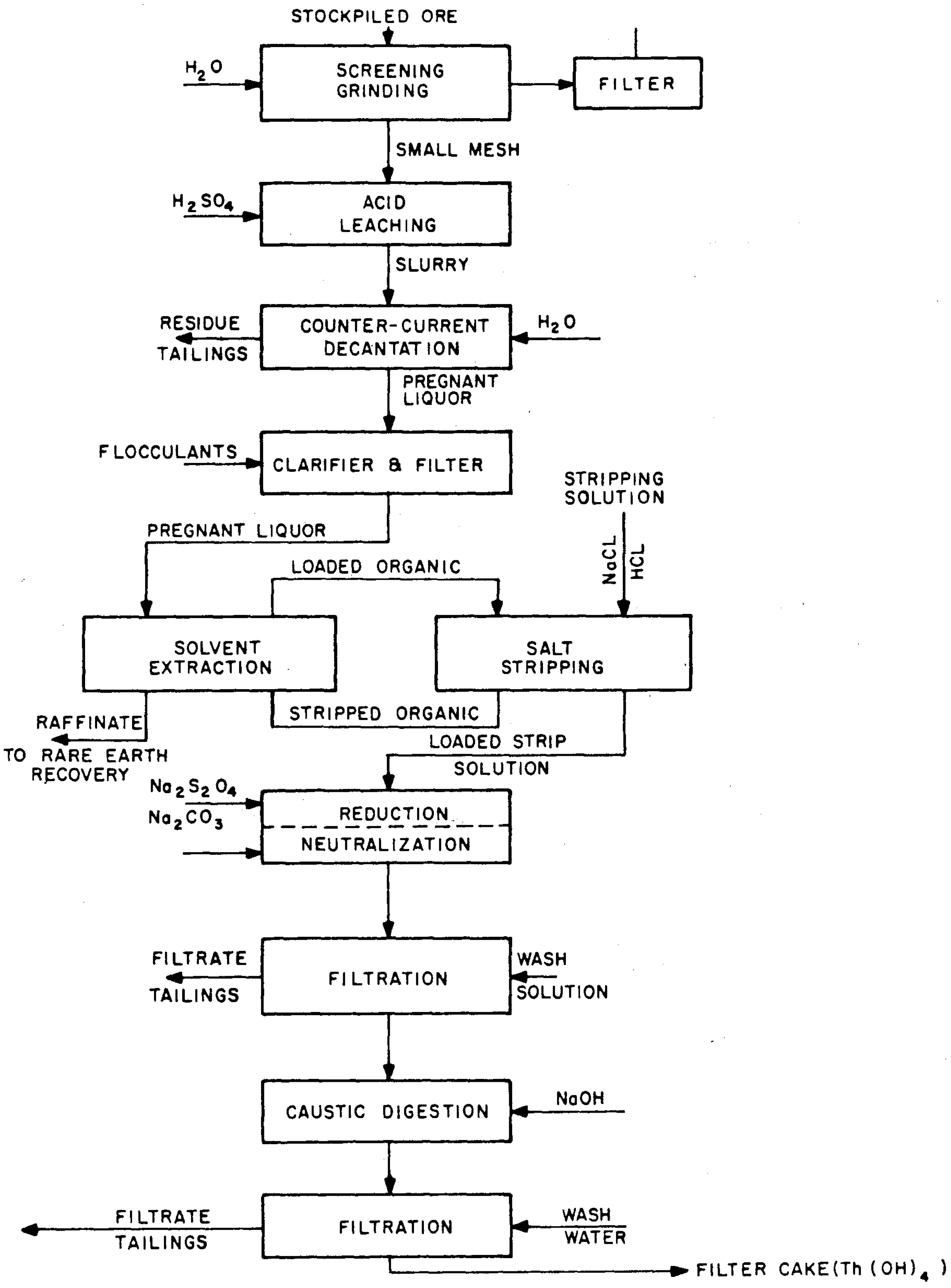


Figure 3. Thorium Milling Flow Sheet.

## SPECIFIC MANAGEMENT METHODS FOR URANIUM MILL TAILINGS DISPOSAL

### Physical Nature of Tailings

The slurry of leached rock and uranium ore discharged from the mill, sometimes after neutralization, usually contains at least 50o/o solids by weight. Some of the tailings liquid may be recycled for use as process water in the mill.

Tailings solids are usually classified as:

(a) sands, consisting of solids of particle size greater than 75 microns
(b) slimes, consisting of solids of particle size less than 75 microns

The ratio of slimes to sands depends on the nature of the ore and the degree of fine grinding in the mill; clay based ores and/or intensive grinding both lead to an increased slimes fraction in tailings solids.
Slimes may constitute typically 20-35o/o of the tailings by weight; they can contain 70-90o/o of the radium and gamma emitting isotopes.

### Transport of Tailings

The tailings slurry is usually pumped through steel or plastic pipes to the tailings retention system. The tailings pipe is fitted with pressure and/or flow alarm indicators to warn in the event of pipe blockage or rupture and the pipe is usually constructed over a corridor for collection and recycle of spillages to the tailings retention system.

### Designs of Tailings Retention Systems

Tailings may be disposed of either into above ground engineered structures, or into below ground excavations which may include open-cut pits, or in special excavations.

### Above ground disposal

Disposal of tailings in above ground retention systems has been the conventional practice to date. The retention systems may, in flat terrain, be constructed as 4-sided structures with embankment walls 10-30 m high. Construction materials may include waste rock and overburden or specifically excavated material. Advantages of topography may be taken by construction of dams or embankments in naturally undulating terrain (USNRC 1979).

Seepage of contaminated water from above ground retention systems is inevitable. The permeability of the base and walls to liquor seepage may be reduced by grouting or lining with material such as clays, which may also be selected on their ion-exchange capacity further to reduce egress of dissolved radioactivity in seepage waters from the retention system. Clay linings may be 0.3-1 m in thickness.

Toe drains may be constructed to collect seepage waters flowing through the sides of embankments and allow their pumping back to the retention system during the life of the mine and mill. Rehabilitation of above ground systems would include dewatering and graded cover to inhibit rain infiltration, to minimize the degree of seepage after closure of the mine and mill (Fig. 4).

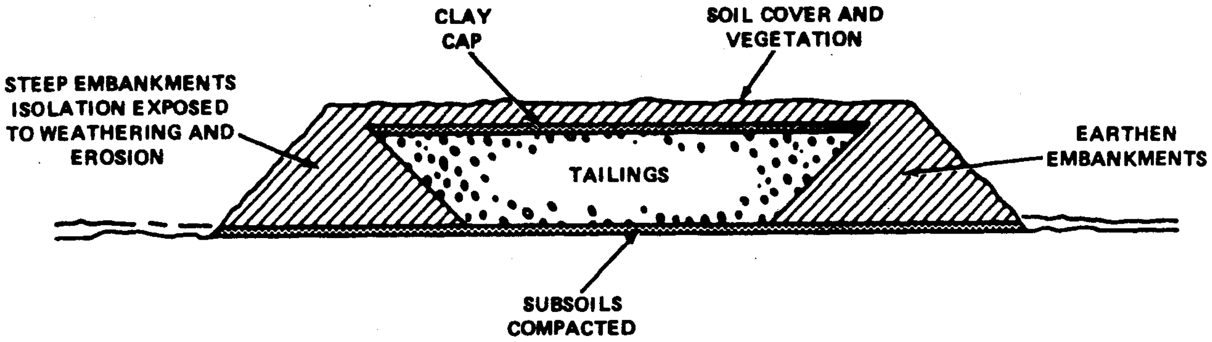
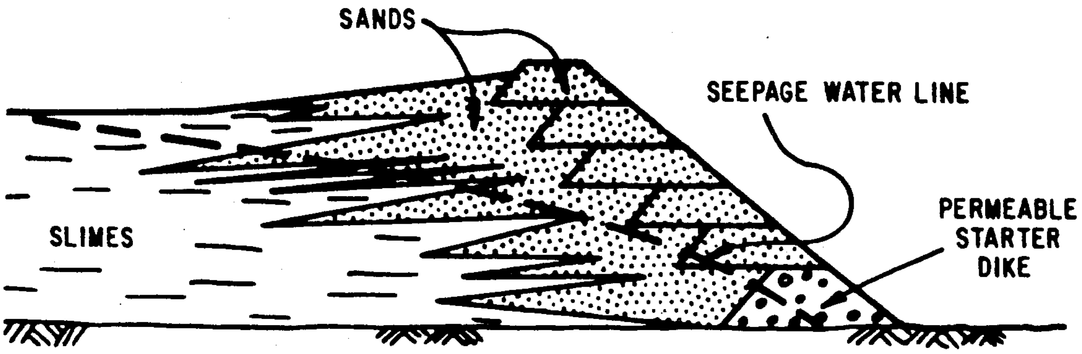


Figure 4. Above Ground Disposal of Tailings

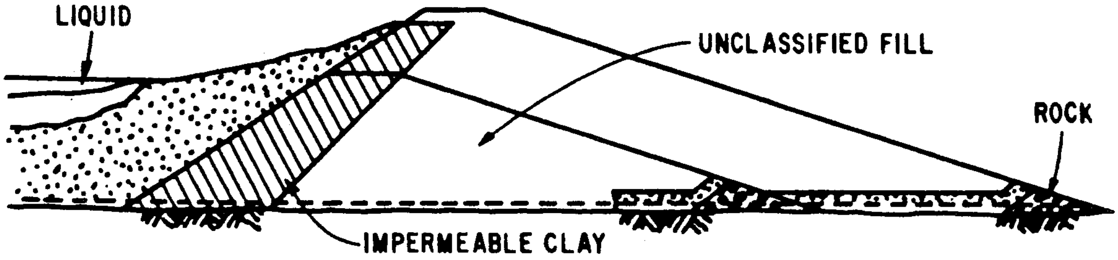
Three methods are available for stagewise construction of above ground tailings retention systems, (a) Upstream Construction, (b) Downstream Construction, (c) Centreline Construction. The different principles employed (USNRC 1979, Volpe 1980) are shown in Figure 5.

Upstream Construction
This is the oldest and most economical method for disposing of tailings. A starter dike is constructed at the downstream toe of the ultimate retention system. The crest of the system is raised by placing fill materials on the upstream side of the starter dike. The centreline of the embankment crest is shifted toward the upstream pond area as the height of the dam increases. The downstream toe of each subsequent dike is supported on the top of the previous dike, with the upstream portion of the dike placed over finer tailings (slimes) within the impoundment. The upstream construction method has the major disadvantage of potential liquefaction of saturated slimes through seismic shock, causing failure of the system; as its height increases, the outside shell contributes less to stablility.

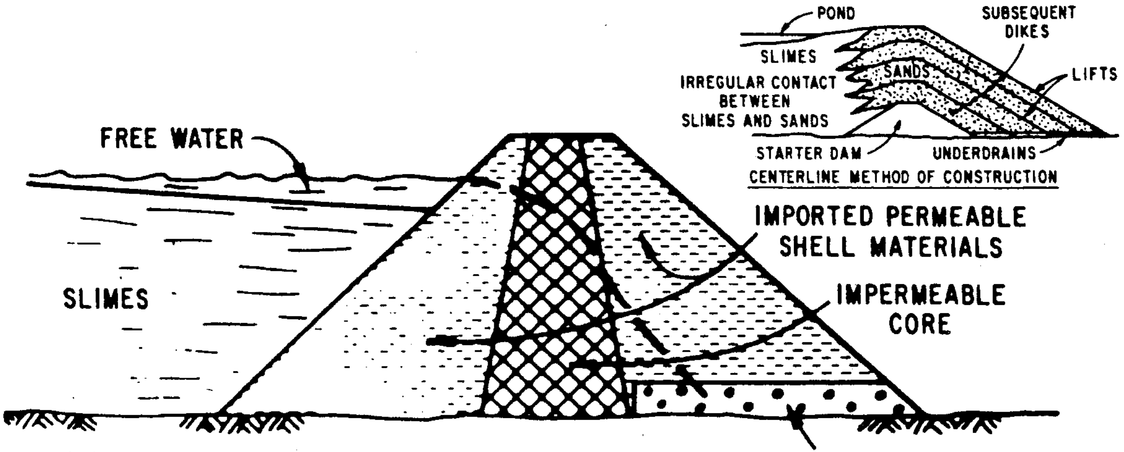
- Downstream Construction
An initial starter dike is constructed at the upstream toe of the ultimate dam. The crest of the dam is raised by placing fill materials in successive dikes located on the downstream side of the starter dike. The centreline of the dam crest is shifted downstream as the dam is raised. Each subsequent stage of dike construction is supported on the top of the downstream slope of the previous section. All of the embankment section lies outside the boundaries of the sediment tailings. Downstream construction features controlled placement and compaction, achieves high shear strengths and resistance to seismic shocks, and has been preferred on safety grounds in the US.



(A) UPSTREAM CONSTRUCTION



(B) DOWNSTREAM CONSTRUCTION



(C) CENTERLINE CONSTRUCTION

Figure 5. Basic Methods of Tailings Embankment Construction

- Centreline construction
  This method is intermediate between upstream and downstream methods. The crest of the embankment is maintained in approximately the same horizontal position as the embankment is raised to is final height. The dam is raised by spreading and compacting successive layers of materials on the crest, on the upstream shoulder, and on the downstream slope. The centreline method permits the downstream half of the tailing dam to be designed and constructed to conventially acceptable engineering standards; however, certain portions of upstream slopes rest over the slimes and are therefore vulnerable to failure through liquefaction from seismic shock.

Below ground disposal

Return of tailings to an open cut (Fig. 6) mine may offer advantages in some circumstances. Sequential disposal operations may be conducted in a large open cut, by construction of temporary dams between the back fill and active mining areas. However the finely divided tailings have a packed volume generally about 30°/o greater than that of the excavated ore, and it may not always be possible to return all of the material to the original excavation. This applies particularly to the case of underground mining. Special problems of water inflow and seepage from the filled open cut may arise in monsoonal areas where the water table fluctuates up to ground level during part of the year. Lining of the pit with clay type materials may be necessary to reduce permeability and seepage (USNRC 1979).

Developments in tailings disposal

As noted earlier, the slimes contain the greater part of the radioactivity. Separation of the slimes from the sands is being considered in some countries as a possible alternative; slimes could be dried, mixed with a solidification agent, e.g. Portland cement or asphalt for burial in underground mines or open cuts. This approach could have advantages in reducing radon gas emission and leaching of radioactivity from tailings.

Robinsky (1980) has claimed that thickening of tailings to about 65°/o w/w solids prior to storage in a tailings dam has advantages over conventional above ground retention systems including

- reduction in capital and operating costs
- reduction of pollution from seepage and wind erosion
- facilitation of rehabilitation of the tailings area.

Storage of thickened tailings has been in operation at a mine in Ontario since 1973, and Robinsky claims that twelve other plants have either adopted this approach, or plan to convert to it in the future.

Burial of dried sands and slimes without separation is also being advocated. Tailings would be dewatered to a semi-dry cake (20°/o moisture content) by equipment such as a vacuum belt filter, followed by a belt conveyor for transport of tailings to the burial area. Advantages of dewatering tailings have been claimed in elimination of horizontal seepage from the retention system, and also elimination of the drying out period at rehabilitation. These advantages might however be negated in monsoonal areas having a high and fluctuating water table level; the additional capital costs of the alternative systems require comparison on a site-specific basis with the claimed benefits (Fig. 7).

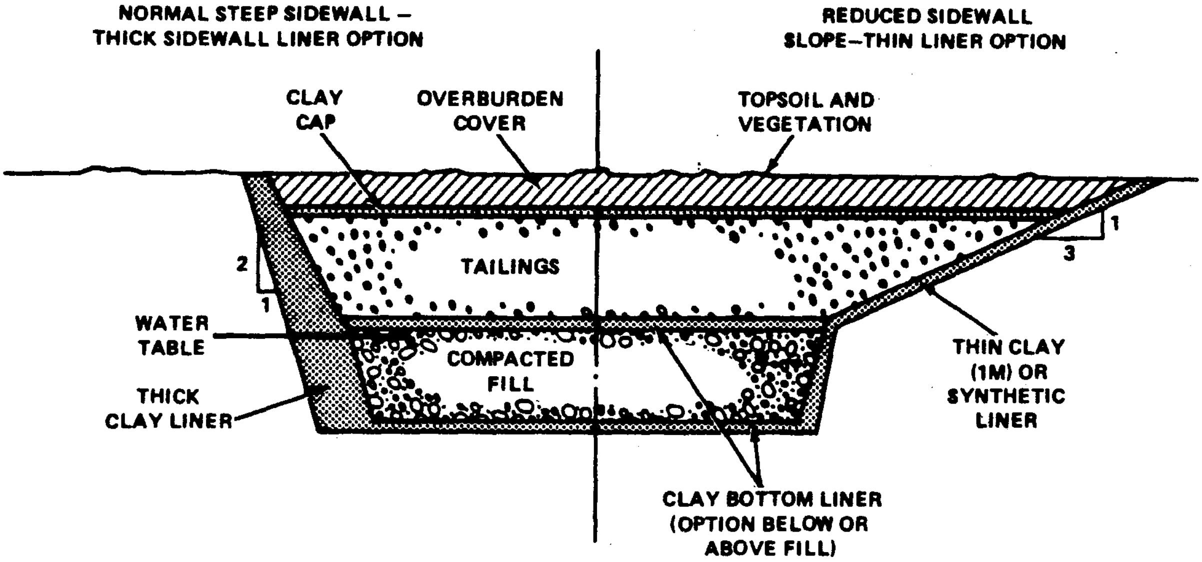


Figure 6. Disposal of Tailings Slurry in Available Open Pit Mine.

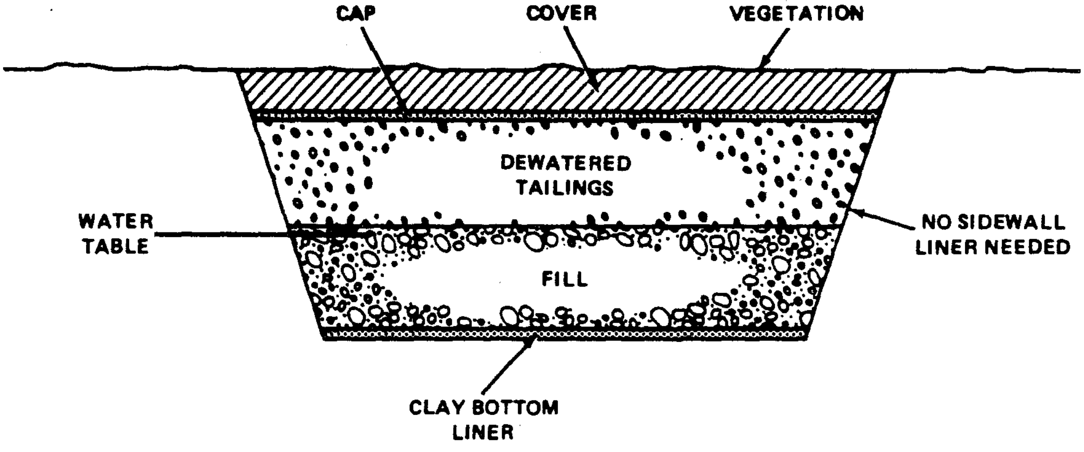


Figure 7. Disposal of Dewatered Tailings in Available Open Pit Mine

## LONG TERM ASPECTS OF URANIUM MILL TAILINGS MANAGEMENT

### Radiological Aspects

The radiological concern in long term management (i.e. disposal) of uranium mill tailings is the potential for exposure of members of the public to radiation through :

(a) emission of radon gas from the surface of the rehabilitated tailings,
(b) leaching of radioactivity (e.g. radium) from the solid tailings and seepage of water containing radium into ground waters external to the tailings site.
(c) possible long term dispersion of tailings through the action of natural forces (erosion, ground movement, flooding, glaciation).

This concern is intimately linked to the long half-lives of some radionuclides, e.g.

| | | |
|---|---|---|
| $U^{238}$ | - | $4.5 \times 10^{9}$ years |
| $U^{234}$ | - | $2.5 \times 10^{5}$ years |
| $Th^{230}$ | - | $8 \times 10^{4}$ years |
| $Pb^{210}$ | - | 22 years |
| $Th^{232}$ | - | $1.4 \times 10^{10}$ years |
| $Ra^{226}$ | - | 1620 years |

Although up to 95°/o of the uranium may be removed in the milling process, the daughter products such as thorium-230 still remain in the tailings and continues to generate and sustain the amount of radium-226 in the tailings. Radium-226 may be leached into rainwater percolating into the retention system and appear in ground waters through seepage processes. A proportion of the radon-222 gas generated from radium-226 in the pile may be exhaled to atmosphere. The concentrations at which the radionuclides enter drinking water courses and the air environment determine the relative hazard of these elements to man.

### Meaning of "Long Term"

The goal of acceptable tailings management is to achieve a "walk-away" situation involving no active continuing surveillance or intervention. The main issues of the definition of long term apper to be :

(1) the existence of institutional controls, and the ability to carry out remedial measures should they be considered necessary;
(2) the assumption that the tailings retention system will perform substantially as designed through its design life.

On this basis, "long term" would commence when active (positive, intentional) management and surveillance of a rehabilitated site ends. This surveillance could be continued until it had been ascertained that the design performance objectives of the stabilisation and rehabilitation program had been achieved.

The duration of the "long term" period for prediction of environmental and radiological impacts of the tailings is less clearly defined. In the absence of a consensus view, it seems generally to refer to an indefinite period extending into the future, although the realistic application of such a definition may be considered to be doubtful.

The absolute containment of tailings either in engineered or natural basins cannot be assured over the time periods of concern. However, it is possible to design and build containments with a reasonable estimate of the time in which some dissemination of the radionuclides could occur, and to predict their rates of dissemination and impact over this period. The IAEA Technical Advisory Group on Current Practices for Tailings Management has considered the "design life" (of a tailings impoundment structure) to be the period during which the tailings impoundment performs as designed with respect to the rates of releases of radionuclides and the retention of tailings material. (Typically of the order of one hundred and several hundred years).

The group considered "long term" to be the period, beyond the design life, for which climatological and geomorphological processes are more or less predictable and would not substantially affect the integrity of the impoundment system. (Typically of the order of 1000 to 10,000 years.)

The latter definition here was specifically intended not to include the period beyond the quoted period of 1000 to 10,000 years.

A realistic period for mathematical modelling of impacts from tailings, would seem, by the limitation on prediction of the climatological and geomorphological processes, inevitably to be restricted to about 10,000 years, although this point is still under debate.

## INTERNATIONAL AND NATIONAL PERCEPTIONS ON DISPOSAL OF RADIOACTIVE TAILINGS

### International Organizations

Both the IAEA and the OECD Nuclear Energy Agency are conducting complementary programs of work on disposal of uranium mill tailings.

### The International atomic Energy Agency

In 1976, the IAEA issued a Code of Practice on the Management of Wastes from the Mining and Milling of Uranium and Thorium Ores, as a result of a request from the United Nations Conference on the Human Environment in 1972. The Code of Practice reflected best available technology at the time, and was recommended by the Board of the IAEA for reference in formulation of national regulations and recommendations. The Agency is currently reviewing practices and options for confinement of uranium mill tailings.

The Agency completed in 1980 a Co-ordinated Research Program on "The source, distribution, movement and deposition of radium in aquifers", in which Australia participated together with about 8 other countries involved in uranium mining. Expressions of interest have been invited by the IAEA for participation in a proposed 3 year co-ordinated program "Environmental migration of radium and other contaminants present in liquid and solid wastes from the mining and milling of uranium".

### The OECD Nuclear Energy Agency

The NEA has had an active work program on occupational and environmental radiation protection and waste management in uranium mining and milling since 1976. Three major Scientific meetings held by the NEA were:

- Specialist Meetings in Dosimetry and Monitoring of Radon and Radon Daughter Products (Elliott Lake, Canada, 1976, and subsequently at Paris/La Crouzille, (1978)
- Seminar on Management, Stabilization and Environmental Impact of Uranium Mill Tailings (Albuquerque, US, 1978)

Following the Albuquerque Seminar, the NEA convened a Co-ordinating Group on the Management of Uranium Mill Tailings to conduct a 3 year collaborative program under the auspices of two main line committees on radiation protection and environmental protection. This program is being conducted in co-operation with the IAEA and other interantional organizations. Ten countries (including Australia) are participating in the program, which has the following objectives:

- to study the long-term aspects of uranium mill tailings management, to formulate radiological protection and radioactive waste management principles for their long-term management, and to develop long-term radiological protection performance objectives and criteria for tailings retention systems based on the ICRP system of dose limitation;
- to develop a comprehensive methodology for comparative evaluation of alternative tailings retention systems based on the optimisation of radiological protection;
- to identify factors and parameters which are generic components of the problems, and to identify separately factors and parameters which cater for site-specific differences for utilisation in development of national licensing and regulatory policies;
- to review critically the technology of the management of uranium mill tailings with performance objectives and criteria for long-term disposal in mind;
- to study and recommend what remains to be done in the engineering of uranium mill tailings retention facilities in order to meet long-term radiological protection performance objectives and criteria;
- to review the techniques of and requirements for physico-chemical environmental monitoring which is required for assessing the long-term environmental impact associated with uranium mill tailings;
- to consider and make recommendations on the scientific aspects of design and operation of such monitoring programs for the purpose of ensuring that long-term radiological (and non-radiological) performance objectives and criteria are met.

In addition to co-ordination of the study, the NEA have undertaken:

- an information exchange about developments in both problems and solutions in participating countries;
- co-ordination of research and development on specific projects in participating countries;
- organization of Workshops, Seminars and other Scientific Meetings on this subject.

The work is directed towards the production of guidelines and state of art reports on the long term aspects of management of wastes from uranium mining and milling.

## Some National Attitudes towards Tailings Disposal Practices

The most recent national views on alternatives for disposal of radioactive tailings material were presented at the First International Conference on Uranium Mine Waste Disposal in Vancouver, 1980.

### U.S.A.

Disposal of tailings below ground level, (i.e. returned to open cuts or special excavation), is regarded by the US Nuclear Regulatory Commission as the "prime option" for most US conditions (USNRC 1979). Examples of below-ground tailings management programs in the U.S. have been reviewed by Scarano (1980). The Commission recognised however that below ground disposal might not be the most environmentally sound approach in all cases, e.g. where high quality groundwater sources lay relatively close to the surface and/or were not well isolated by overlying soil; also that near surface bedrock could lead to impractical costs of excavation. The key point in favour of below ground disposal was its relative insusceptibility to natural erosional forces. Major requirements from the USNRC Draft Generic Environmental Impact on Uranium Milling, (which might be considered the US equivalent of the Ranger Uranium Environmental Inquiry), were as follows (USNRC 1979):

#### Decommissioning and Rehabilitation

- Radon emanation to be reduced to near background levels in non uranium bearing areas (2 pCi $m^{-2}$ $s^{-1}$) (0.7 Bq $m^{-2}$ $s^{-1}$) by a minimum earth cover of 3 metres over tailings.
- Protection of groundwater and minimization of seepage by use of liners in the retention system.
- Below ground disposal recommended to (a) avoid need for active maintenance, (b) prevent erosion of tailings, (c) allow rehabilitation for unrestricted use.

#### Institutional Requirements

- Abandoned mine/mill sites to be government owned.
- A one-time charge of at least $250,000 to be made on each mining company before granting mining leases, to provide financial security for decommissioning.

#### Site Selection

- Objective to optimise remoteness of disposal site from populated areas and to optimise hydro geologic and other conditions to isolate contaminants from usable groundwater sources.

### Canada

Control of radon and its daughter products has not been regarded as so critical in wet (Canadian) climates as in dry climates; gradual leaching of radium-226 from the surface into the centre of the tailings will decrease the rate of radon emanation. Clay type materials with natural ion-exchange mechanisms for radionuclides in the uranium decay chain probably present the best opportunity for ensuring long term control of release rates of radioactivity to the environment.

Regulatory criteria under consideration by the Canadian Goverment, based on minimum acceptable standards in Canada (Bragg 1980) include the following:

- The long term durability of alternative disposal systems must be evaluated and the degree of maintenance reduced to the minimum practical extent; long term performance and economic guarantees will be required.
- Use of natural barriers (e.g. clays, etc.) to control releases from abandoned sites; surface water input to sites to consist only of direct rainfall without a permanent pool on the area.

- Limitation of access to abandoned sites to prevent removal of tailings or construction of dwellings.
- A cover of 2.0-2.5 metres of soil over the tailings for erosion control and reduction of radon emission to levels in the range 2-10pCi $m^{-2}s^{-1}$ (0.07-0.4 $Bqm^{-2}s^{-1}$); particulate emissions from tailings must be virtually non-existent.
- Limitation of gamma radiation flux from the tailings (coverage required for erosion and radon control should be adequate).
- Water release following rehabilitation to be less than during operation.

### Australia

As noted later, the appropriate Australian Code of Practice has not reached the final drafting stage. Probably Australia's main concern is to ensure that international guidelines at present being drafted fully reflect the requirements of and management options most appropriate to Australian conditions. For this reason, Australia is making a major input to the OECD/NEA Collaborative Study on Uranium Mill Tailings Management.

## URANIUM MINING EXPERIENCE AND DEVELOPMENTS IN AUSTRALIA

Mining and milling wastes have arisen in the past in Australia and will arise in large quantities following the development of new uranium mines and mills.

### Past Operations

The quantities of tailings existing in Australia from old mining and milling operations are as follows:

In the Northern Territory three mills, Rum Jungle, Moline and Rockhole, processed uranium ores. These operations ranged in size from small to very small:

Rum Jungle - 2990 tonnes of uranium between 1954-1971
Moline - 440 tonnes of uranium between 1959-1964
Rockhole - 117 tonnes of uranium between 1959-1962

and employed essentially identical methods of tailings disposal management. Tailings were discharged onto convenient areas where the contained water drained off leaving the tailings on the surface. As the amount of tailings built up, small earth embankments were built to prevent the tailings from entering the local watercourses. These efforts were generally not successful (as the structures were insufficiently sized and poorly constructed) and at Rum Jungle during the latter stages of operations this method was abandoned in favour of discharging tailings into holes left by previous open cut mining activities.

In Queensland, the mill at Mary Kathleen Uranium produced 3500 tonnes of uranium from ores between 1958 to 1963. After a shutdown period of 11 years, a modified mill was recommissioned in 1974 and had produced about 2250 tonnes of uranium to 30 June 1980. The tailings disposal area consists of two main sections: a tailings dam where solids are deposited, and a lower containment area where liquid wastes are evaporated.

In South Australia, uranium ore from the Radium Hill mine was physically beneficiated and transported to a treatment plant at Port Pirie. An amount of 720 tonnes of uranium were produced during 1954 to 1962. Tailings are contained in an earth-clay embankment situated on tidal mud flats.

The quantities of tailings generated at the five mills were as follows:

Rum Jungle - 1,150,000 tonnes
Moline - 128,000 tonnes
Mary Kathleen Uranium - 4,800,000 tonnes

Radium Hill/ Port Pirie - 970,000 tonnes

No attempt has been made to date at any of the sites to rehabilitate the disposal areas either during operations or after they ceased. Rehabilitation of the Rum Jungle site is planned for the early 1980's.

## Problems Arising from Some Past Disposal Practices in Australia

In the Northern Territory, problems arising from disposal of uranium tailings have been relatively minor with the exception of the situation as regards the Rum Jungle operations. At the three mill sites noted above, uranium tailings were eroded into watercourses adjacent to disposal areas. At the Moline and Rockhole mills, the quantities of tailings involved were relatively small. At Rockhole, the eroding tailings entered a relatively deep waterhole of the South Alligator River. During the monsoonal dry season, the concentration of radium-226 in this waterbody is about 3 pCi L-1 and increased concentrations of radium in fish and reptiles have been observed. It is assumed that the seasonal flushing of the South Alligator River by monsoonal floods would limit the geographical extent of the radiological impact arising from the tailings at Rockhole.

At Rum Jungle, however, some uranium tailings were discharged into the East Finniss River, and material leached from the tailings, overburden heaps and open cuts enters the East Finniss during the annual wet season. Surveys have found significant levels of radium-226 in and adjacent to the River for tens of kilometres below the mill site. On the land, this contaminant has become tied up in grasses and the soil while the concentrations of radium-226 in waters of the east branch of the Finniss River have, at times, been found to exceed drinking water standards recommended by the International Commission on Radiological Protection.

Aside from radioactive contamination, heavy metals and low pH have also presented problems. At Moline, tailings containing heavy metals and sulphides in high concentrations have caused destruction of vegetation in the tailings area and for a short distance below the area. However, this appears to be the limit of the gross effects as no fish-kills are known to have resulted from the operations. At Rockhole, there was an absence of appreciable quantities of heavy metals and sulphides in the tailings; consequently, problems associated with these did not appear. At Rum Jungle the effects of heavy metal and pH pollution were, and still are, quite marked and of major significance. Besides the tailings, process liquors (in earlier days) and waste rock dumps have contributed large quantities of heavy metals and acids to the pollutant load from the site. This is due to the nature of the waste rock dumps which contain pyritic shales and other sulphide ores. The oxidation of these materials is linked to the activity of thionic bacteria which produce ferric sulphate, an aggressive solvent of sulphides. These reactions liberate heavy metals from the waste rock which are ultimately transported into the Finniss River system during the wet season.

Pollution by heavy metals and sulphides contained in the ores processed at Rum Jungle caused destruction of vegetation and largely eliminated aquatic life in the East Finniss River during mining operations. Continuing pollution does not appear to be causing further damage to vegetation but fish-kills occur at the beginning of each wet season near the confluence of the East Finniss River with the Finniss River some tens of kilometres downstream from the mine site.

Finally, at each of the sites mentioned the disposal of tailings (and in the case of Rum Jungle, overburden and below-grade ore) created an aesthetic eyesore which could remain for many years in the absence of rehabilitation efforts.

The Commonwealth Government has made Budget provision for a comprehensive program of rehabiltation at Rum Jungle designed to reduce continuing pollution originating from the mine site and to provide for aesthetic rehabilitation by landscaping and establishment of permanent vegetation. The Government's 1980/81 Budget makes provision for a program estimated to cost $12 million over four years. Site investigation work to enable preparation of detailed design for the rehabilitation program is being planned.

In the absence of rehabilitation programs at Moline and Rockhole, leaching of contaminants will continue on the basis of decreasing yield. Wherever contaminants in the tailings do not inhibit re-growth of vegetation, erosion of these materials should gradually decrease to some low base value. Eyesores will be gradually eliminated as vegetation is able to re-establish itself on the tailings area.

## Present Developments and Intentions for Tailings Disposal

The major Australian uranium resources and the quantities of tailings estimated for disposal are listed in Table 3. Development of all the resources shown would require the disposal of about 140 million tonnes of tailings, together with over 200 million tonnes of waste rock.

Tailings will be disposed of at the mine sites by storage in surface retention dams, in the mine excavation, or by a combination of both methods.

An acidic tailings slurry (pH 2.0) is discharged from the Mary Kathleen mill (Queensland), into an aboveground disposal dam where solids are deposited. Water is decanted from the tailings dam into two surface evaporation ponds. Rehabilitation at mill closure may involve allowing the ponds to dry, transfer of deposited salts to the tailings dam, followed by revegetation.

All mills in the Alligator Rivers Uranium Province (Northern Territory) are required to have a plan of management for disposal of tailings which must receive approval from the Government agencies supervising such operations. The disposal system employed or contemplated involve sub-grade disposal in either abandoned open cut mining pits, or special excavations, above grade disposal behind dams, or partial subgrade disposal in special excavations supplemented by low dams. However, these systems are subject to three important provisos. They must:

(1) unless discharge is allowed under special authorisation, be capable of containing all contaminated water from the mining and milling operations areas for the duration of the project;
(2) provide for rehabilitation either at the end of operations at the site, or at intervals during the course of operations;
(3) be engineered systems which utilise best practical technology and have a logical progression considering and caring for all the factors of containment of wastes, control of pollution, safety of operation, and contingencies of operations at the mine and mill.

TABLE 3

MAJOR AUSTRALIAN URANIUM RESOURCES

| OREBODY | LOCATION | AVERAGE ORE GRADE (%$U_3O_8$) | CONTAINED URANIUM t U | PROPOSED MINING TECHNIQUE | ORE TREATMENT PROCESS | QUANTITY OF TAILINGS t x $10^3$ | QUANTITY OF WASTE ROCK t x $10^3$ | COMPANY OR ORGANISATION |
|---|---|---|---|---|---|---|---|---|
| **Koongarra No.1** | Northern Territory | 0.27 | 11,300 | Open-cut | Acid-leach; amine solvent extraction | 4,940 | 7,400 | Denison Mines Ltd.* |
| **Nabarlek** | " | 1.84 | 7,700 | Open-cut | " | 490 | 4,000 | Queensland Mines Ltd. |
| **Jabiluka No.1** | " | 0.25 | 2,900 | Underground | " | 1,370 | 10,400 | Pancontinental Mining Ltd.* and |
| **Jabiluka No.2** | " | 0.39 | 173,000 | Underground | " | 52,300 | | Getty Oil Development Co. Ltd. |
| **Ranger No.1** | " | 0.30 | 43,900 | Open-cut | " | 17,250 | 135,000 | Peko-Wallsend Operations Ltd. |
| **Ranger No.3** | " | 0.22 | 41,600 | Open-cut | " | 23,000 | | Electrolytic Zinc Aust. Pty. Ltd. |
| **Yeelirrie** | West Australia | 0.14 | 39,000 | | Carbonate-leach | 27,000 | 29,700 | Western Mining Corporation |
| **Mary Kathleen** | Queensland | 0.12 | 6,000 | Open-cut | Acid leach; amine solvent extraction | 5,900 | 17,700 | Mary Kathleen Uranium Ltd. |
| **Beverley** | South Australia | 0.26 | 13,500 | - | - | 5,200 | - | Western Nuclear Ltd.* |
| Honeymoon | " | 0.16 | 2,870 | Solution mining | | * * | - | Mines Administration P/L * |

*Awaiting development approval

** Solid waste 17,200 t; Liquid waste 3250 $m^3$

Nabarlek is the only operational uranium mine and mill in the Northern Territory at the present time. Neutralised tailings from the Nabarlek mill are treated with barium chloride solution to facilitate precipitation of radium before disposal of the tailings in the Nabarlek open cut. Tailings from the Ranger and Koongarra mills will be neutralised and stored in retention dams designed to minimise seepage and remain stable under all likely climatic and seismic conditions. Tailings from the retention dam at Ranger will be returned to the No. 1 open cut pit unless otherwise mutually agreed by the Commonwealth Government, the Northern Land Council, and the Ranger Management. It is proposed that, following recovery of gold from Jabiluka tailings, about 50o/o of tailings as sands will be returned to the underground excavation as cemented fill, and the remainder as slimes stored in a surface retention dam.

Rehabilitation of surface tailings dams, worked out mines, and some waste rock piles containing potential sources of pollution will be necessary at the closure of a mine and its mill. This rehabilitation must be designed to achieve long term radiological and environmental protection without the need for long term human intervention.

## RELEVANT LEGISLATIVE DEVELOPMENTS IN AUSTRALIA

### Code of Practice for Management of Wastes from Mining and Milling Radioactive Ores

A draft Australian Code of Practice on Management of Wastes containing Radioactive Material from Mining and Milling of Radioactive Ores is being prepared jointly by the Commonwealth Government, State Governments and relevant Statutory Authorities. The Code of Practice is being formulated pursuant to the provisions of Section 7 of the Environmental Protection (Nuclear Codes) Act 1978. The Code will address management of contaminated waste, airborne and liquid effluents which may contain significant amounts of radioactivity as a result of the mining and milling of uranium and thorium ores. "Significant" amounts of radioactivity in this context are those quantities and/or concentrations of radioactive materials considered to contribute a potential hazard to public health and safety, and requiring observance of standards specified in the Code of Radiation Protection in the Mining and Milling of Radioactive Ores.

While the details of the Code are yet to be agreed, it is to be expected that it will provide guidelines to the following topics:-

- Review of Types of Radioactive wastes needing Management Procedures, including those resulting from opencut, underground and solution mining.
- Procedures for Management of the Radioactive Content of these wastes, including the cost effectiveness of alternative Management Procedures under conditions likely to be faced in Australia.
- Procedures for decommissioning and rehabilitation of mines, mills and tailings retention systems after closure of operations, including site surveillance, monitoring procedures and their duration.
- Legal and Financial responsibilities for decommissioned tailing sites.

### Environmental Requirements

Pending promulgation of the code of practice, large scale development of uranium deposits in the Alligator Rivers Region of the Australian Northern Territory are proceeding under Environmental Requirements specified individually for each development and backed by appropriate legislative acts and regulations (OSS 1979). Thus the Environmental Requirements for development of the Jabiru ore body (Ranger Uranium Mines, Ltd) were contained in an authorization issued by the Minister for Trade and Resources under Section 41 of the Atomic Energy Act 1953. Environmental Requirements for development of the Nabarlek ore body (Queensland Mines Ltd.) were contained in Special Mineral Lease No. 94, issued by the Northern Territory Minister for Mines and Energy.

These Environmental Requirements stipulate that mining and milling operations including management of wastes be carried out in accordance with 'best practicable technology', defined as "that technology from time to time which produces the minimum environmental pollution and degredation that can reasonable be achieved" having regard to:

- Comparable levels of achievement in the uranium industry anywhere in the world.
- The cost of application relative to the level of protection to be achieved.
- Evidence of (or lack of) detriment after project commencement.
- Physical location of the project.
- Age of equipment and facilities.
- Social factors.

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