Technical Memorandum 48

A review of worldwide practices for disposal of uranium mill tailings

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Supervising Scientist for
the Alligator Rivers Region

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Abstract

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The world's ever increasing need for energy has led to the construction of over 400 nuclear power stations since 1950. The fuel for these plants is processed from uranium which is mined in about 18 countries. The milling of uranium ore produces a waste product, the mill tailings, which contains about 85% of the ore's original radioactivity, process reagent residues and often a wide range of heavy metals, all of which have the potential to degrade the environment. The risk to human health and the environment has only been fully appreciated in relatively recent times. Earlier disposal plans for uranium mill tailings were frequently inadequate and resulted in adverse environmental impact.

This review explains the nature of the risks to the environment and human health before describing many of the past disposal practices associated with uranium mill tailings. Current uranium mill tailings disposal practices in the major producer countries are then described, including remedial actions that have been undertaken to alleviate problems arising from earlier, inadequate and/or inappropriate disposal programs. A range of options available for tailings disposal is presented, together with a brief overview of legislation and regulations from a number of countries. Finally the report looks at how the issue might be addressed in the Alligator Rivers Region of Australia.

Summary

There are over 400 power stations in the world which rely on uranium as their fuel source. The mining and milling of the uranium fuel's raw material is a process which leaves behind substantial volumes of a radioactive waste product, the uranium mill tailings. Today there are probably more than 500 million tonnes of uranium mill tailings located in 18 countries around the world. In earlier times these process residues were often not disposed of in a thoughtful manner but abandoned at the most convenient location. Growing public awareness of the need to protect and preserve the natural environment, coupled with knowledge of the possible hazards to public health, has led to the introduction of procedures to ensure that the contamination is minimised and hazards reduced as much as possible. The prime health hazards during the operational phase and in the short term after mine close-out relate to radon emanations and the carcinogenic properties of the decay products of radon. Over the long term the concern is the release, by erosion and transport, of radionuclides and their possible subsequent ingestion by biota, including human beings. There are also health hazards related to gamma radiation, dust and possible contamination of water supplies by radionuclides and heavy metals. They are identified and discussed in this review.

Published literature relating to uranium mill tailings is limited. Examination of the available literature has shown that there are a variety of ways that this issue has been tackled in the past. Today there are three main objectives commonly considered in designing and operating containments for uranium mill tailings. Firstly, the tailings themselves must be contained in a structure that is assured of a long life, usually taken to mean at least 1000 years. Secondly, the groundwater resources of the area around the containment must be protected from contamination by the tailings or any leachates arising from the tailings; and thirdly, there must be a requirement for only minimal maintenance of the containment facility after the construction phase has been completed. In many locations the requirement is for a maintenance-free containment structure. The decision as to whether the best location for a containment is above or below grade is one which has to be site specific. There are examples of both simple and sophisticated schemes for placing tailings in old mine pits as well as some very complex above-grade structures.

The standards applied to establish the success of containment can be either very prescriptive as is the case in the United States, or site specific and risk-based which is the tendency in Australia. Some countries, eg Spain and Niger, have codes and standards which draw heavily on the experience and regulations already established in the USA and elsewhere, with a few local additions.

Within Australia there are three active uranium mines. At the Nabarlek site the tailings have been placed in the mine pit and close-out is planned for late 1995. At the Ranger uranium mine the present tailings containment is an above-grade structure built to exacting standards, as if it were a water retaining structure. The present regulations require that this structure and the enclosed tailings be returned to a mine pit at the end of operations. The mining company has indicated that they are looking into the option of rehabilitating the structure and tailings in situ, ie above-grade. The criterion for the choice of location is that the supervising authorities are satisfied that the environment will be no less well protected by this alternative scheme. The Olympic Dam mine tailings are deposited in an above ground containment which is intended to be the final repository. This containment is built as a conventional tailings dam using upstream construction methods.

This report gathers information on world-wide practice, with the objective of assessing the best solution to disposal and containment of uranium mill tailings in the Alligator Rivers Region, within the context of best practicable technology as defined and applied in the region. In particular, the criteria to be considered when assessing the in-pit disposal option are listed and

discussed. No attempt is made to determine best practicable technology for the industry in general, owing to the great variety of site-specific conditions.

The conclusion is that an in-pit or below-grade disposal system may be considered as the 'prime option' in terms of long term environmental protection. This is provided that the containment site meets standards regarding groundwater contamination and geological stability.

In respect of the Alligator Rivers Region, the selection of a below-grade site and the introduction of site specific criteria rather than prescriptive standards would seem to be the most suitable option. This would enable the guidelines of the Australian Code of Practice to be met. However, the final decision will lie with the supervising authorities after the determination of what is 'best practicable technology' for these circumstances. Finally, the review lists 51 references.

Glossary

Above or below grade	Above or below original ground surface
ARR	Alligator Rivers Region
BPT	Best practicable technology
Bq	Becquerel — SI unit of radioactivity, the activity of a quantity of radioactive material where 1 nucleus decays per second
Ci	Curie — unit of radioactivity, equivalent to 3.700×10^{10} decays per second. Now replaced by the Becquerel: $1Bq = 2.7 \times 10^{-11}$ Ci
Cyclone	Centrifugal separation of water and solid components of a slurry
ER	Environmental Requirements — (of the Commonwealth Government, applying to the Ranger and Nabarlek mines)
ERA	Energy Resources of Australia Ltd — operators of the Ranger Uranium Mine
Gy	Gray — the SI unit of absorbed dose of radioactivity: 1Gy = 1 Joule/kg
IAEA	International Atomic Energy Agency — a part of the United Nations
QMPL	Queensland Mines Proprietary Limited — operators of the Nabarlek Uranium Mine
Rip-rap	Size-graded boulders used for erosion control
RUM	Ranger Uranium Mine
Sv	Sievert — Unit of radiation dose; effectively a measure of human biological risk resulting from radiation exposure, normalised to the whole body

A review of worldwide practices for disposal of uranium mill tailings

Introduction

This report reviews past and current practices for uranium mill tailings disposal throughout the world, and compares them to current practice in Australia. It also makes comparisons between the legislated Environmental Requirements (ERs) pertaining to uranium waste disposal in the Alligator Rivers Region (ARR), and the Australian Code of Practice on the Management of Radioactive Wastes from the Mining and Milling of Radioactive Ores (AGPS, 1987), and legislation in place elsewhere in the world.

This review was undertaken as part of the process of evaluating what is 'best practicable technology' (BPT) in the Alligator Rivers Region of Australia. BPT is a concept that is defined in the Environmental Requirements which are applied to the mining of uranium in that region to ensure that the environment is adequately protected from the mining and milling processes. The definition of BPT is given in Appendix A.

In 1992 world uranium production was 36 000 tonnes (Robertson Australia, 1993). Although production has been declining since the late 1980s it has been predicted that by the year 2000 the annual demand for uranium will be steady at about 54 000 tonnes, of which 49 000 tonnes will need to be produced from mines, the balance coming from re-processing of nuclear products (Bahr, 1993). Throughout the world there are 18 countries, including the former 'Eastern Block' and China, where uranium ores are being mined and processed (IAEA, 1992). Eight of these countries have the capacity to produce more than 1000 tonnes of uranium annually. The process residue is described as mill tailings, a radioactive waste product.

Apart from literature searches, both manual and electronic, a simple questionnaire was distributed to a number of major uranium mining companies and regulating agencies throughout the world. There were also discussions with colleagues and associates from the uranium mining industry and regulating authorities both in Australia and overseas. The questionnaire was not wholly successful as there were no replies from Russia, Eastern Europe, China and most of the minor producing countries.

Uranium mill tailings

The current annual world production of uranium mill tailings has been estimated at more than 20 million tonnes (IAEA, 1992). The country with possibly the largest amount of uranium mill tailings is the USA where, by 1979, a total of more than 22 million tonnes of tailings had been abandoned, exposed and untreated, at sites throughout the country (UMTRA, 1991). A further 173 million tonnes were estimated to be at active mills in 1982 and this is likely to exceed 200 million tonnes by the year 2000 (Groelsema, 1982). The country with the next largest amount of tailings is probably Canada, which was estimated by Hamel and Howieson (1982) to have approximately 130 million tonnes of uranium mill tailings.

Tailings mostly have the texture of a fine sand and represent about 98% by volume of the material extracted during mining. They contain about 85% of the radioactivity found in the original rock with radium being the main source of this radioactivity. The milling and extraction process removes about 95% of the uranium and 15% of the total radioactivity from the ore material. These are transported from site in the product, uranium oxide (U_3O_8), known as yellowcake. The remaining 5% uranium and 85% of the original radioactivity stay in the process residue with thorium 230 as the dominant long lived radionuclide. As the short lived daughter products such as thorium (^{234}Th) decay (it has a half-life of 24.1 days), radioactivity is quickly reduced to about 75% of the original level. Many of the remaining radionuclides in tailings have very long half-lives, for example 80 000 years in the case of ^{230}Th and 247 000 years for ^{234}U. As a result of these half-life times, although the concentration of radioactivity in tailings may be low, some degree of associated radiological hazard can be considered to last forever.

Sources and hazards

The safe disposal of tailings has become the focus of public concern mainly because of the environmental impact and health risks inherent in several of the disposal methods used in the past. The tailings were often pumped from mills as a slurry and deposited on the ground surface adjacent to the mill areas as piles resting at their natural angle of repose. In other locations tailings have been deposited into lakes and waterways, mined-out pits or valley fill sites and various types of ring-dyke impoundments. These impoundments often employed conventional upstream construction methods that are commonly used for tailings dams. This involves building each successive lift of the tailings impoundment wall using the previously deposited tailings as a foundation. The health hazards occur in a number of pathways via radioactive gas emanation, gamma radiation, radioactive dust and through contamination of surface and ground water.

A further source of process residues is heap leach piles. At these sites rock materials containing very low ore grades have been piled up and suitable leaching solutions, usually acids (although alkalis have also been used), allowed to percolate through — dissolving up uranium on the way. The pregnant solution is then treated to extract the uranium and the depleted ore is left as a pile of waste which is radioactive and a potential source of contamination. The characteristics of the piles are very different to those of tailings. The size distribution of the heap leach material is coarser as the ore is only crushed not ground; commonly D_{80} is about 20 mm rather than the 0.2 mm or less found in tailings. The heap leach piles stand above ground on prepared impermeable pads and are not contained in dams or pits. The piles contain only ore, no chemical reagents are added other than the leaching solution. In contrast tailings frequently contain residues of oxidising agents, extracting/leaching solutions and neutralants.

Although not tailings, these heap leach piles also require rehabilitation. Many of the methods employed in their rehabilitation are similar to those used for tailings.

In the post-operational phase few sites had any containment or covering procedures other than simple rock, earth or bituminous covers. Some piles were left totally uncovered at this stage, whilst others were covered with topsoil and revegetated. Some tailings piles have been reworked for further uranium (eg Falls City, Texas) or other minerals such as gold by heap leaching or re-milling (eg Moline, Australia) and others were even used as a source of building material (eg Grand Junction, Colorado). Some tailings disposal sites have become point sources of contamination either directly through radioactive emanations, by physical impact of the spread of tailings, or through contamination of surface and ground waters by seepage containing radionuclides, heavy minerals and the products of acid mine drainage (IAEA, 1992).

Disposal options

Regardless of their origin, ie from operating or abandoned mines, from open pits or underground mines, there are four options for disposing of uranium mill tailings that are currently considered appropriate by authorities (IAEA, 1992):

- containment in a specially designed and constructed impoundment.
- dispersal into the environment at a safe rate as agreed by the operators and the regulating authorities.
- removal of the more contaminated portion thus reducing the volume of contaminated material to be contained; for example concentration of radium, and possibly other radionuclides, into a slimes fraction which could then be cycloned off and contained, leaving the less contaminating sand fraction in place. Such technologies are still in the research stage and are certainly not well enough developed to permit removal of controls on the disposal of the sand fraction (IAEA, 1992).
- changing the form of the tailings so that the contaminants will not be released to the environment so readily. This may involve trying to alter the physical state of the tailings, eg use of cement to produce an artificial rock-like material with better erosion resistance than 'untreated' tailings; sintering tailings at high temperatures to alter their structure and reduce radon emanations (Dreesen et al, 1982); also changing the chemical state of the tailings, eg by using additions, such as lime, to cause precipitation of heavy metals and reduce the possibility of their leaching from the containment.

The most common practice both currently and in the past is the first option, ie to impound tailings in a location at the surface. Elements of the other three options are frequently employed, such as the use of a neutralant, or coarse fractions cycloned off and so on; mixing tailings with cement to reduce erodibility of the overall mass has also been proposed. Whichever basic method is chosen the common objective in contemporary situations is to reduce, as far as possible, the hazards to human health and the environment posed by tailings.

Hazards associated with uranium tailings

Community concerns about health risks and a growing awareness of the need to arrest environmental degradation have led to a series of programs in some countries, including the United States, France and Australia, to try and contain the tailings in a safe and effective manner. These programs are dealing with both the relic tailings of past operations as well as formulating procedures for current and future operations. The legacies of the past are the major cause for concern. In the USA the realisation that there was a health hazard associated with the tailings occurred in the 1970s. This resulted in the introduction of new legislation as well as a change in environmental planning rules which have required more recent and current mines to plan for safe and appropriate tailings disposal. These rules apply from the beginning of operations and cover both the operational and post mining phases.

The potential environmental and health hazards that may arise from dispersal of, or public exposure to, uranium mill tailings are:

- gamma radiation;
- contamination of food and water by dust and particulate matter;
- contamination of ground and surface waters by solutes originating from tailings, particularly heavy metals and radionuclides such as Radium 226;

- radon progeny – these are the carcinogenic decay products of radon, a radioactive gas produced by radium;
- physic: :pact in waterways and on vegetation of the deposition of tailings eroded from a containment;
- products of acid rock drainage in ground and surface waters.

Radiological hazards

The hazard to health arising from exposure to tailings increases with the length of the exposure time. For example, gamma radiation levels are generally low and prolonged exposure approaching full time (24 hours per day) would be needed before the worker dose limit would be exceeded. Such prolonged exposure could eventually lead to an increased risk of cancer, particularly leukaemia and gastro-intestinal cancers. The radioactive decay series found in tailings gives rise to a range of products and the half lives of some of the radioactive components are very long, often thousands of years. Gamma radiation rates measured at the surface over tailings can vary from < 2Sv.hr^{-1} to 60Sv.hr^{-1} depending on the density and coarseness of the tailings. Coarser tailings radiate lower levels of gamma (Robertson et al, 1987). The moisture content of the tailings also has an effect on radiation levels, radon emanations increasing as tailings dry out (IAEA, 1992).

One of the most significant radionuclides is ^{230}Thorium which has a half life of 80 000 years and decays to give ^{226}Radium which in turn gives rise to ^{222}Radon, then other radon progeny. These include ^{210}Lead and radioactive bismuth and polonium, which pose a potentially significant health risk especially in relation to lung cancer and leukaemia. Many of the other radioactive components of tailings have long half lives, so effectively the risk is perpetual (UMTRA, 1991). Radon emanation rates vary greatly with the ore grade of the source material of the tailings. Tailings from low grade ore may emanate 1–5 Bq.m^{-2}s^{-1} whilst high grade deposits may give up to 60 Bq.m^{-2}s^{-1}. However, proper and thorough rehabilitation can significantly reduce the health hazard due to radon. On a site at Beaverlodge in Canada the predicted dose from a revegetated tailings area was estimated as 0.001 Sv.yr^{-1} (Robertson et al, 1987).[1] However, radon emanation rate and dose rate cannot be compared directly as meteorological conditions and critical group considerations vary from site to site.

Thus it is necessary to limit public exposure as much as possible, certainly below the recommended dose limit of 1 mSv per year (ICRP, 1977). This is generally achieved by containing the tailings for as long as possible.

There is a risk of uptake of radionuclides by other pathways such as in foodstuffs, both animal and vegetable, or water that has become contaminated. Also there is the risk of direct ingestion of contaminated material; this applies particularly to small children who, for example, might regard uncovered tailings as sand-filled play areas. Similarly traditional land owners cooking in the embers of open fires could ingest tailings primarily as dust, but also with the food, if the fireplace were located on a tailings deposit.

Non-radiological hazards

The non-radiological components of tailings can also pose a hazard to health and the environment. The nature of the processes used in the milling of the ore may result in increased availability of a wide range of heavy metals in the tailings, or the residues of process reagents may have the potential to cause adverse environmental impact. Chemical constituents such as sulphate, ammonia, chloride, pyrite, kerosene and sulphuric acid are all commonly found in uranium mill

1 The units for strength of radiological source and radiation dose are given in the Glossary.

tailings (Pidgeon, 1982). The transport of these chemicals into the environment through aquatic or atmospheric dispersion needs to be controlled and kept to the absolute minimum achievable using best practicable technology and the 'as low as reasonably achievable' principle (ALARA). The increased levels of heavy metals in ground and/or surface waters may impact upon drinking or irrigation water supplies which in turn could lead to increased dietary uptake by humans. The increased intake of heavy metals can pose a serious health hazard, especially for children and animals.

Other processes that might act on uranium mill tailings to produce hazardous conditions from a human health standpoint are climate, biological processes and chemico–mineralogical changes. Furthermore, many of the contaminants, especially the heavy metals, retain the same levels of toxicity permanently, unlike the radionuclides which gradually decay and become less dangerous with time.

Past practice for uranium mill tailings disposal

There are several ways in which the disposal of uranium mill tailings has been handled in the past:

- in a valley, usually behind a dam or dyke;
- within a custom-built ring-dyke or turkey nest dam;
- returned to a mined-out pit;
- in a custom-built pit or repository;
- returned to an underground mine;
- into a deep lake or river.

Examples of each of these methods are discussed below country by country.

Past practice in Australia

South Alligator Mill, Northern Territory

In the early days of uranium processing in Australia, during the 1950s, tailings were not considered to be a particularly problematical waste. For example, at the South Alligator mill the tailings were deposited un-neutralised on a flat area immediately downhill of the mill and adjacent to the South Alligator River. There was no serious attempt to retain tailings, and observers from that time comment that tailings often went into the river as a consequence of flooding during the Wet season (R. Fry, pers comm).

Moline, Northern Territory

At this site, the tailings were derived from a series of mining operations near Moline and from the South Alligator area, approximately 37 km to the east, for copper and gold as well as uranium. Within the total tailings volume there are approximately 6000 tonnes of uranium tailings from the South Alligator mill, which were relocated to Moline and reprocessed for gold in 1987. Earlier mining operations at the Northern Hercules mill and mine, adjacent to the Moline site, had produced between 1959 and 1972 about 246 000 tonnes of uranium–copper–gold tailings. These tailings were deposited un-neutralised behind bunds adjacent to the Northern Hercules mill. These bunds were simple structures made of earth pushed up by bulldozers and failure of the walls was common. Subsequent erosion at the site resulted in about 25% of the tailings being carried away into Tailings Creek, thence to Eureka Creek and eventually to the Mary River floodplain. The result of these erosion events was that only approximately 174 000 tonnes of tailings remained by 1983 (OSS Annual Report, 1986). The radioactivity of the tailings differed: South Alligator tailings had a radon emanation of 6 Bq $m^{-2}s^{-1}$ whereas the mixed Moline tailings had an emanation of 2 Bq $m^{-2}s^{-1}$ [illegible] differences were a function of the different uranium ore grades and mineral processing streams. The tailings repository was capped by contractors under the supervision of the Northern Territory Department of Mines and Energy later in the 1991/2 period and covered with a rock mulch as erosion protection.

Rum Jungle, Northern Territory

From 1952 until 1963 uranium was mined at a number of workings on this site, with milling continuing until 1972. Copper was also mined from 1952 until 1965. Tailings were deposited un-neutralised into a series of small impoundments, with simple earth dams, behind a dam wall which enclosed a small valley approximately 800 meters long by a maximum of 500 metres wide. The individual impoundments were not interconnected but the tailings did overtop the small embankments. The total amount of tailings deposited was 600 000 tonnes spread over an area of about 31 ha. Supernatant liquid, which also contained some suspended tailings, was allowed to drain over a spillway whence it flowed into the Finniss River. There was also some wind dispersal of tailings (Verhoeven, 1988).

From time to time there were breaches of the dam which resulted in considerable volumes of tailings being released to the river system. An initial clean-up program in 1977 dealt mainly with aesthetic matters but failed to address the issue of containment of pollutants (Kraatz & Applegate, 1992). In the hazard remediation program completed in 1986 tailings and contaminated soil were placed in the Dyson's Open Cut. No special preparation of the pit was undertaken prior to placement of the tailings. The tailings were covered with a 1 metre thick rock blanket and then alternating layers of contaminated subsoil and copper heap leach pile material, from the copper leach pad site. All the heap leach material was disposed of in this way. The pit was then sealed and vegetated. The tailings dam site was covered with topsoil, surface drainage was installed and the whole area revegetated (Verhoeven, 1988).

The ore bodies at Rum Jungle contained sulphides in such quantities that their hydrolysis and oxidation during weathering produced sufficient sulphuric acid for heavy metals, particularly copper, and low levels of radioactivity to be leached from waste rock and tailings. The tailings also contributed to this contamination but have been estimated to have contributed only about 5% of the copper load which was so destructive to the aquatic ecosystem of the Finniss River. It has also been suggested that sulphuric acid residues in the tailings contributed to the contamination of the river (J. Fisher, pers comm).

Radium Hill, South Australia

Uranium mining began in 1954 at Radium Hill approximately 120 km south-west of Broken Hill. The ore was concentrated by a flotation method and railed 250 km to Port Pirie on the Spencer Gulf where yellowcake was produced by an acid leach and ion exchange process. The operation ceased in 1962. There were two tailings dams at the mine site, covering about 40 ha. By 1981 one of the tailings heaps had suffered extensive erosion as gullying, and wind-blown tailings were dispersed over a wide area. A second tailings heap had been partially covered with waste rock prior to the site being abandoned and was in considerably better condition. Concerns about the spread of radioactive dust from the tailings heap led to a rehabilitation program being undertaken in 1981. The tailings surfaces were sealed with a compacted clay layer 1 metre thick and the old dam structures surrounded by compacted clay walls 9 metre thick at the base thinning to 3 metre at the top. Rock armouring of the structures was not carried out because it was considered to be too expensive. At the time construction was finished a 20 year maintenance period was considered necessary (Cannon, 1990).

There were other processing residues at another site in Port Pirie as a consequence of the uranium milling and yellowcake production. These were also a cause of public concern due to dusting and frequent public ingress to the site. Relocation of these materials to the Radium Hill site was discounted on the grounds of cost, as was the possibility of importing suitable fill materials to construct an *in-situ* cover. However, a local lead–zinc smelting plant in Port Pirie offered to supply free slag from the smelter for use as a cover. This was in exchange for the rights to dump material on the land occupied by the uranium processing wastes, which included some uranium mill tailings. Slag was placed over the pile to a final depth of 1.5 metre which prevented dusting and reduced radon emanation levels to below the USEPA recommended limit for rehabilitated uranium tailings piles (Cannon, 1990).

Mary Kathleen, Queensland

This facility mined ore from 1958 to 1963 and again from 1976 to 1982. Unlike the other Australian uranium mines described above, Mary Kathleen was rehabilitated at a time when public awareness of environmental issues had grown and the need for proper rehabilitation planning was seen as paramount. The rehabilitation included not only the mine, the tailings dam, evaporation ponds and the process plant but also the township. The overall objective of the plan was to leave the site in a safe and stable state consistent with the proposed future land use (rangeland grazing) and with no restrictions on public access due to radiation levels. The general principle of the works was that they should comply with the code of practice (AGPS, 1987). Although not clearly stated in the company literature on rehabilitation, this would imply that the design life of the containment was 200 years and the structural life 1000 years.

Within the overall rehabilitation plan the tailings area became the repository for all the contaminated wastes and liquids. About 7 million tonnes of tailings covered an area of approximately 28.5 ha. The tailings surfaces were graded to slopes of 0.5% leading into perimeter drains. The initial intention was to place 1 metre of waste rock on this surface to provide erosion protection, shield radiation and reduce radon emanations. This procedure was carried out over about 60% of the upper south section of the tailings dam. At this stage of the work it was established that improved control of radon could be achieved using a 500 mm layer of clay and soil. As a consequence the waste rock was removed and replaced by a compacted 500 mm layer of clay and soil taken from the uncontaminated portion of the evaporation dam wall; the 1 metre thick waste rock layer was then replaced. On the upper north area a 500 mm layer of contaminated clay, soil and evaporites from the floors of the evaporation ponds was spread over the tailings surface; this was followed by 500 mm of clean soil and clay and, finally, 1 metre of waste rock.

The lower north section of the tailings dam had been used as an evaporation pond and, as the pond free water area decreased due to evaporation, slimes, evaporite and contaminated soil materials were tipped around the perimeter. Radionuclides and salts were precipitated from the residual liquid using lime. After a period of drying the area was covered with 500 mm of soil/clay and 1 m of waste rock.

During production the coarse tailings had been cycloned off and deposited on the downstream side of the main tailings dam wall. During rehabilitation these were levelled out and waste rock was placed on the top of the tailings. The surface provided a minimum cover of 2 metres on a batter slope of 2.5:1; rock cover on the level portion was 1 metre thick, graded at a slope of 0.5% to direct runoff. A final layer of large garnetite boulders was placed over the waste rock as additional erosion protection. At the end of the work a filter zone to trap fine particles washed from the tailings was built beyond the toe of the wall; this filter was covered by a 2 metre layer of compacted waste rock topped with large boulders (Mary Kathleen Uranium Ltd, 1986).

Examples of past practice in other countries

As part of this review, information on uranium mill tailings disposal was sought from the major producers amongst the 17 other countries besides Australia where uranium milling is undertaken.

These countries included Canada, the United States, Niger, Gabon, Namibia, France, South Africa and Russia. Much of the information is not easily available and only a few countries and companies were willing to provide data. A simple questionnaire was distributed to major uranium milling facilities but there were few replies. In particular there were no responses from Russia, China or eastern European nations. There are few records in the literature giving details of uranium mill tailings disposal systems, much more emphasis being given to disposal of high level radioactive wastes.

USA

This section briefly describes selected locations from amongst the many sites in the USA where uranium mill tailings have been deposited.

At **Grand Junction, Colorado,** 1.9 million tonnes of uranium mill tailings were deposited on a flat area in the centre of town adjacent to the mill. Between 1951 and 1970 these tailings were freely offered to the population as a source of building sand. In recent times over 4500 properties in the town have been declared 'vicinity properties' and have required substantial remedial work to reduce the radiation hazard to below public exposure limits. The tailings and the contaminated materials from these properties have been relocated to a custom built repository at Cheyney, a location about 30 km outside the town.

The repository is an engineered cell, partly below grade, with an area of 24.3 ha (60 acres). It has been excavated into a slope and about 12.5 metres below the existing ground surface into shale beds that are nearly 200 metres thick. The permeability of the shale is between 5.1×10^{-5} and 2.7×10^{-6} $cm.sec^{-1}$, depending on the degree of weathering. The excavated shale has been compacted to form dykes as a liner around the perimeter of the containment zone. Contaminated materials were placed in layers and compacted. The final landform has been constructed to conform with the USEPA stability requirements set down in 40 CFR 192. The side slopes are 1:5 (v:h) and the top slope is graded at 1:50 (v:h). On the 'uphill side' the top slopes are graded into the natural contour. The cover is 1.7 metres thick and multi-layered containing a 600 mm compacted clay radon barrier. The whole surface has been given erosion protection in the form of stone rip-rap. This work was carried out as a program under the Uranium Mill Tailings Rehabilitation Project, supervised by the UMTRA Project staff of the Department of Energy (P.Waggitt, pers obsvn).

At the **Lucky Mc Mine, in the Gas Hills uranium field, Wyoming,** 9.5 million tonnes of tailings were deposited into an unlined pond which was underlain by permeable alluvial deposits of the Lower Wind River. Seepage from the tailings pond has been detected in groundwater at least 1000 metres from the site and an extensive program is underway to prevent further seepage and remediate the groundwater. The program has commenced with the sealing of the source of the seepage. This will be followed by the flushing of the contaminated ground water (Daroussin & Pfiffelmann, 1993). Nearby at a UMECO site in Gas Hills groundwater is being pumped from around an in-pit uranium tailings repository to a reverse osmosis plant. In the plant contaminants, including radionuclides, are removed and the polished water is re-injected to the water table. Slime residues from the osmosis plant are evaporated in a synthetically lined pond with the final dry residue being taken for burial in a containment cell. There is no indication of how long it is intended to continue this process (P.Waggitt, pers obsvn).

An early remediation program was carried out at the **Spook tailings site, Wyoming.** The mine and mill had been abandoned and the US Department of Energy carried out a remedial action project in 1988–89, another example of the UMTRA program. Approximately 173 000 cubic metres of contaminated wastes, including 124 000 cubic metres of tailings, were relocated to a mine pit. In this case a containment cell was constructed in the floor of the pit and the tailings and contaminated waste were deposited in a conventional manner. A 1 metre thick leachate reduction layer was built in the floor of the cell which had side embankments constructed from compacted earth and rock materials from the excavation. The sides of the cell were built with slopes of 1:2 (v:h) and the top surface was graded at slopes of between 1:33(v:h) and 1:12 (v:h). The cell was closed out with a layered low-permeability cover approximately 500 mm thick and 3.3 metre thick granular layer to offer a permeable surround to the completed cell. Finally 1 429 500 cubic metres of waste rock and overburden were used to backfill the pit. The average depth of this rock cover was about 17 metres (Morrison-Knudsen Engineers, 1988).

One of the largest sites in the USA is the **Kerr-McGee mill at Grants, New Mexico**, with over 30 million tonnes of tailings deposited above ground in a conventional turkey nest type structure built using upstream construction. This method describes where successive lifts of the embankment wall are built using the dried tailings as a foundation, ie the structure gradually becomes narrower as its height increases. Such constructions are commonly used for tailings dams where there is no requirement to contain water. This site has been mothballed awaiting an improvement in market conditions. The tailings repository has been covered over much of its surface with an earth rock cover, but could be reactivated very quickly. There is a comprehensive seepage collector system and the final plan calls for a multi-layer cover incorporating a radon barrier. The final erosion protection layer will be rip-rap rather than an earth/rock cover. Side slopes are approximately 1:5 (v:h) as required by the USEPA in 40 CFR 192.

Also in **New Mexico**, the nearby **Homestake** mining operation is in rehabilitation. Also an above-ground repository built by upstream methods this site is interesting for the water management operations. Excess water from the tailings pond and seepage collector system is evaporated with the assistance of sprinkler systems in both the tailings decant pond and a custom-built evaporation pond. Seepage waters are also treated by reverse osmosis and chemical additions to remove heavy metals before being re-injected into the shallow aquifer. The final plan for the tailings is a typical multi-layer cover incorporating a radon barrier. The side slopes will be built in accordance with the USEPA requirements of 40 CFR 192, ie slopes of 1:5 (v:h) and erosion protection in the form of rip-rap.

Canada

In 1987 there were approximately 43 million tonnes of uranium mill tailings at 15 abandoned sites in Canada (Robertson et al, 1987). Examination of the literature has revealed that in the early days tailings were often neutralised with lime to about pH 8 (to increase precipitation of heavy metals) and deposited in small lakes or swamps. Where suitable 'natural receptacles' did not exist, tailings dams were commonly built of gravel or waste rock so as to ensure free drainage. In all cases the solid material was retained and the clear decant liquid was allowed to overflow into a natural water course or body. Whenever acid conditions became established the resultant levels of heavy metals in solution often had serious environmental consequences (Ritcey, 1989; Uranium Institute, 1991).

The Canadian Government sponsored a large research program from 1982 to 1987 called the National Uranium Tailings Program (NUTP). The prime purpose of this program was to provide an information base to the government which would assist in the long term protection of the environment. The program was in three sections, Modelling, Measurements and Disposal Technology and a final report was published in 1987 (John, 1987). The major outcome was a mathematical model for predicting possible environmental impacts arising from uranium mill tailings repositories and the application of the model to a site at Lacnor, in Ontario province.

France

The uranium mining and milling industry in France is relatively young and has benefited from the lessons learned from earlier operations elsewhere in the world. Many facilities date only from the 1970s which means that environmental concerns about tailings and environmental impact were already appreciated. Tailings disposal systems were implemented with emphasis being placed on protecting the environment. Certainly environmental programs are in place at several locations. For example, at **Le Cellier** tailings were layered in the pit with waste rock on either side of a central draining waste rock dam. There is no information available about the preparation of the pit, or groundwater conditions in and around the pit, prior to deposition of tailings. The final cover was a compacted layer of waste rock with a soil layer of unknown thickness (Daroussin & Pfiffelmann, 1993).

Sweden

At **Pleutajokk**, in the north of the country, tailings are deposited above-grade in a small valley impoundment. Tailings are handled in an essentially dry form at about 15% moisture content. The disposal site has been lined with a crushed rock filter so that drainage waters can be collected and treated before discharge to the environment. Tailings arrive by conveyor and are spread and compacted in layers about 200 mm thick with side slopes of 1:3(V:H) to reduce the risk of slide failures. A 3 metre thick layer of glacial till is then placed over the site as a final cover and revegetated with natural forest.

At **Ranstad** in south western Sweden tailings were backfilled into worked-out parts of the shallow open pit. This created a facility where the tailings were impounded below ground level but relatively high up in the landscape. Tailings arrived by truck with about 17% moisture content and were placed and compacted in 1000 mm layers on a drainage bed of alum shale and limestone fragments. The containment was within a double dam structure and a minimum till layer of 300 mm was applied to the top as a cover. At the end of the operation the groundwater was allowed to rise within the containment to the level of the outer dam wall thus keeping the tailings saturated. It is anticipated that seepage through the tailings will be very slow and the release of contaminants into the environment will be at a rate too slow to result in significant environmental impact (Eurenius et al, 1982).

Spain

The mill at **Andújar** was operational from 1959 until 1981, producing 1.2 million tons of solid waste all of which was placed in a tailings pile (Uranium Institute, 1991). The pile covered an area of 9.4 ha and had a volume of 980 000 cubic metres with a maximum height of 20 metres. A decommissioning program was begun in 1987 and finalised in 1988. Details of the program have been extensively described by Caldwell and Reith (1993). The design standards imposed by the Spanish Nuclear Safety Council were based on the provisions of the USEPA and ICRP for the most part.

Initially the tailings pile was reshaped and stabilised and contaminated mill arisings were stacked in an adjoining pile. The whole heap was covered with a layer of soil as a means of reducing radon emanations. Finally a multi-layer cover was placed which is intended to provide a growing medium for climax vegetation on the top and a soil matrix in amongst the riprap to promote revegetation on the side slopes. Side slopes were 1:5 to provide stability without the need for very large diameter rip-rap as erosion protection. The layers included drainage and filter sections as well as a radon barrier and a biointrusion layer of gravel and rock to impede animal and plant penetration.

There were specific groundwater protection provisions put in place requiring that radionuclide concentrations at the site boundary (the point of compliance) should not be exceeded for at least 10 years. This site is adjacent to a river and the design includes flood protection works. The surrounding land use is olive groves with an olive oil processing plant in the vicinity. The company is also required to monitor the situation for a minimum of 10 years to confirm performance of structures and demonstrate compliance with the established concentration limits (Caldwell & Reith, 1993).

India

The main centre for uranium mining and milling is at **Jaduguda in Bihar State**. Tailings were neutralised with lime and cycloned. The sand fraction was used as backfill in the mine while the slimes were pumped together with liquid mill wastes as a slurry to a 12.25 ha tailings pond. The pond is a natural valley site which drains over an earthen dam. The decant liquid which drains from the tailings discharges into a stream and thence to the Gara River. This liquid has a neutral pH but contains radium and manganese at levels in excess of drinking water standards, and has high levels of magnesium and calcium. Work has been undertaken to improve the quality of effluent waters (Kharbanda et al, 1982).

Germany

As mentioned earlier, almost no published information could be located on uranium mill tailings disposal methods in the former eastern European countries. Nor did any agencies there reply to the request for information. However, as a consequence of the political changes that have followed the re-unification of Germany some material has begun to appear. Keller (1993) has made some references to the environmental impacts arising from uranium mining in his published work on radiological impacts from all forms of mining in the Saxon Erzgebirge area. It appears that from 1946 and 1989 a joint venture of the former East German and Soviet Union Governments mined about 220 000 tonnes of uranium in the provinces of Saxony and Thuringia, located south west of Berlin. The operation employed about 150 000 workers at 400 shafts and up to 15 mills. Tailings disposal was uncontrolled and much material was used in construction of dwellings to offset shortages of conventional building materials, especially concrete sand. Keller (op cit) was studying the health implications and impacts but notes that the tailings were frequently dispersed by wind and water following erosion. He reports radon concentrations in houses built from waste and tailings 'of several thousands of Bq/m^3'.

Summary of past practice for uranium mill tailings disposal

In the past tailings were often simply abandoned rather than managed and their final resting place was rarely in facilities designed to last for more than a few years. Little attention was paid to the environmental consequences of these actions. Many countries have now realised the error of their ways and have taken steps to remediate the situation. In the USA the Uranium Mill Tailings Remedial Action Project (UMTRA) has been underway since 1978. This program remediates abandoned uranium mill tailings piles. Also it is now appreciated that a tailings pile or waste rock dump that is apparently physically and chemically stable at the end of rehabilitation works, may undergo drastic changes in both characteristics within a relatively short space of time (Richards, 1993). Consequently design parameters are changing to meet the requirements of codes of practice which call for a design life of 200 years and a structural life of 1000 years for containment structures. This is best seen in such programs as UMTRA in the USA and the NUTP in Canada as well as the Australian Code of Practice (AGPS, 1987). The risk to human and environmental health is driving the programs to clean up abandoned tailings sites with work being undertaken at all levels of government. For example in northern Australia the abandoned sites have been cleaned up by the Federal Government, State Governments have regulatory responsibility for current tailings piles, and local councils have assumed responsibility for maintenance on rehabilitated sites.

Current practice in uranium mill tailings disposal

Australia

Australia has a history of rehabilitation of uranium mill tailings that shows a progressive development in techniques and standards from the minimalist strategies of the 1950s, through the post-operation planned approach of the early 80s to the totally planned approach of the present time. No new uranium mine could commence operations in Australia nowadays without a comprehensive tailings disposal plan having first been designed to the highest internationally acceptable standards and agreed by the relevant authorities. The previous practices such as indiscriminate dumping and failure to contain contaminated materials coupled with the lessons learned from the impacts seen at such sites as Grand Junction (USA) and Rum Jungle (Australia) and growing public concern about health issues and environmental protection, have led to the introduction of legislation. This has been designed to ensure that operations are carried out using 'best practicable technology' with environmental impacts minimised at all stages. There have been three uranium mines operating in recent times and their tailings disposal systems are described below.

Olympic Dam, South Australia

Tailings are currently deposited in two ring-dyke structures on flat ground covering an area of 75 ha, and 105 ha respectively. The operators have EIS acceptance to extend the facility to 400 ha. The first retaining dyke was initially 7 metres tall and made of below ore grade uraniferous material (BOGUM) and waste rock. Subsequent lifts are in 5 metre increments with a maximum planned height of 30 metres. The structures have walls constructed of waste rock. Both floors and walls are lined with a 1 metre thick layer of a clay like material won from the inter-dune swales. The retention of limestone sub-crops and two sand dunes within the structures has provided paths for water to leave the impoundment at a rate faster than 'normal' seepage. There is no additional seepage control or collection system. Tailings are deposited un-neutralised and sub-aerially from a moveable single point discharge spigot. Some cyloning is carried out to obtain coarse fraction fill for use in underground works at the mine. In the early stages of operations tailings were deposited using a multi-point discharge system to establish an initial beach structure and to maximise evaporation of supernatant liquor.

The target settled density for tailings claimed by the mine's operators is 1.6 to 1.9 $t.m^{-3}$ (Showers, 1990). There is no decant system and water leaves the system by evaporation and seepage. The underlying geology is karst limestone and the groundwater is generally 160 to 200 metres below ground level. The main aquifer is super saline and considered totally unusable for potable, irrigation or stock watering purposes.

In February 1994 it was reported by the mining company that there had been a sudden rise in the water table beneath the tailings dam. Studies carried out by the company and the supervising authorities showed that there were no environmental impacts at the minesite or in the immediate vicinity. The quantity of water that had caused this water table rise was estimated by the company to be about 5 ML (Duncan, 1994). After further investigations the company announced in May 1994 that the tailings evaporation ponds would be modified to reduce seepage losses. The proposed modifications included a new 30 ha evaporation pond with a synthetic membrane liner to be built before the end of 1994 to replace the present pond. Changes to increase evaporation introduced included installation of a sprinkler system to increase the evaporative area. These measures had reduced the seepage rate so that the rate of water table rise beneath the tailings ponds had fallen from 2 metres to 400 mm per year (Robertson, 1994).

The final rehabilitation plan in the EIS was for the tailings pile to be capped with 1.5 metres of clay and 1.5 metres of waste rock, but there was no description of revegetation. It is understood that the original plan is being reviewed with the intention of carrying out tests to see if material volumes, and consequently costs, could be reduced; the revised plan would also address the issue of revegetation (F. Harris, pers comm).

Ranger, Northern Territory

Tailings are neutralised after an acid leach process. Until 1988 tailings were deposited by sub-aqueous methods, but since then sub-aerial methods have been used. The initial requirement was for a 2 metre water barrier to be maintained above the tailings to reduce radon emanations. After research showed that radon emanation from beached tailings was not a significant hazard, the requirement to keep the tailings water-covered was removed. Also removal of the water cover allowed the tailings to achieve a greater settled density. This was considered to be a great benefit as it would allow a greater mass of tailings to be stored in the dam. Until recently sub-aerial deposition was from a series of sequential point discharges along either the north, east or south walls of the tailings dam, resulting in the formation of a series of gently sloping beaches. The total amount of tailings in the dam was estimated to be approximately 12 million tonnes in mid-1993.

In the wet season of 1992/3 the location of the tailings discharge pipe was changed to become a single point discharge from a vertical pipe located towards the centre of the tailings dam. This method has been described in the Australian Guideline *Tailings Impoundment for Uranium Mines* (AGPS, 1987) as the 'coning method' and is based on the ideas of Robinsky (1979). In the 1993/4 wet season the discharge point was relocated to another point near the centre of the pond. The site of the previous discharge is now clearly shown by the presence of a small island of tailings.

The tailings dam is approximately 1 km^2 and is built to water retaining structure standards. The floor of the dam was not lined, although upstream blankets were laid down in some weak and permeable areas to protect the foundations. Seepage was identified as a possible environmental hazard and so a seepage collector system (SCS) was installed. The dam has been lifted on three occasions using downstream construction methods. This means that the new wall has been built on the downstream side of the existing embankment and extends over the previous toe area. As a consequence the SCS has had to be revised and modified each time. After the stage IV lift in 1989 the SCS was replaced by a simpler system that acts also as an interim seepage surveillance system (SSS). Waters collected by all the collector systems have always been temporarily retained in a sump and then pumped back to the tailings dam periodically.

The Ranger Environmental Requirements (ERs), are a set of regulations determined by the Commonwealth Government and appended to the Ranger lease to provide operational guidelines designed to prevent environmental degradation. The ERs are also a schedule to the Uranium Mining (Environment Control) Act (1979), the legislation by which the uranium mining industry is regulated in the Northern Territory. ER 29(a) requires all tailings to be returned to the worked out pits at the cessation of operations unless the Supervising Scientist is satisfied that, by dealing with the tailings in another manner, 'the environment will be no less well protected'. Presently the mine plan is to place tailings arising from future milling operations of ore body No 3 into No 1 pit when it has been mined out. Whilst the mine plan is not yet available it is understood that underdrainage will be installed prior to the placing of tailings. Possibly this practice will commence during the milling campaign of the 1994/5 wet season. It is not clear at the moment if the tailings will be deposited in neutral or acid form, although initially it seems most likely that the present system of neutralisation will continue pending the outcome of a research program by ERA into acid tailings deposition. The final fate of tailings at present in the tailings dam may change as the company has, in the past, indicated that it is considering the option of rehabilitating the tailings dam *in situ*. The final rehabilitated land form would be built over the top of the existing tailings dam with the tailings remaining contained but above ground level. This option is being modelled by the Office of the Supervising Scientist to evaluate the risk that may be associated with erosion of the structure (Riley, 1994).

The whole Ranger minesite has to be rehabilitated in accordance with a goal and objectives agreed by the Federal and Northern Territory governments and the representatives of the traditional land owners (OSS Annual Report 1990–91, p 84). The overall objective is that the site should be rehabilitated to allow its incorporation into the surrounding Kakadu National Park. A series of Technical Working Groups have been set up, composed of representatives of all the agencies and organisations involved from government (both Territory and Federal) and the traditional land owners. The goals include reduction of radiation dose and soil erosion to as close as reasonably achievable to background, and vegetation that matches the surrounding area. The funds to carry out the rehabilitation work are put aside in a trust fund which is re-assessed annually. The final details of the cap for the containment have not yet been finalised but a multi-layer design is most likely.

Nabarlek, Northern Territory

The ore body was mined out in 143 days during the 1979 dry season. The ore was stockpiled under a sprayed concrete cover on a specially built clay-lined pad pending completion of mill construction. In a situation that is probably still unique the tailings were deposited into the pit from which the ore had been extracted, although there are examples of old mine pits being used as tailings repositories (eg Elliot Lake, Canada; Falls City, Texas; and Spook, Wyoming in the USA). The Nabarlek pit was essentially dry with no significant groundwater ingress, hence the placing of tailings was not seen as being likely to lead to contamination of ground water resources in the region. Tailings were initially deposited sub-aqueously after being neutralised to pH 9. In 1985 the deposition method was changed to sub-aerial. This followed the removal of the requirement to maintain a 1 metre deep water layer over the tailings as a radon barrier, and the wish to improve the settled density of the tailings in the pit by using sub-aerial deposition. Discharge points for the tailings were moved between alternate sides of the pit throughout the following years. The milling operation ended in 1989.

In 1990, the tailings surface was allowed to dry out and form a crust. Next a geotextile was laid over the tailings and covered with 1–2 metres of graded waste rock to provide a working platform for the installation of vertical drainage wicks. The wicks were installed on a 3 metre X 3 metre grid to a maximum depth of approximately 33 metres. The wicks drained water as the tailings began to consolidate under their own weight, the weight of the rock blanket and the vibration of the installation machinery. The wicks were still operational in early 1993 after further materials had been deposited in the pit.

Monitoring has shown that there is some seepage of water from the pit as indicated by changes in sulphate levels in adjacent groundwater observation wells, but this has generally been small. The Nabarlek site has to be rehabilitated by 31 December 1995 and decommissioning and rehabilitation work has been underway since 1992. A Decommissioning Working Group made up of representatives from the mining company, Federal and Territory Government agencies and representatives of the traditional land owners has been meeting for some years to plan and oversee the rehabilitation operation. Whilst rehabilitation plans were agreed at the outset of the project, changes in technology and practice elsewhere have resulted in the decommissioning plan being regularly reviewed and updated. The present plan is for the mill arisings and other contaminated materials and unsaleable plant items to be placed in the pit on top of the rock blanket. The pit will then be filled with waste rock and left with a shaped cap above ground designed to shed rainwater. There will be no separate radon barrier in the cap as the zone beneath the cap will be permanently moist. It is anticipated that the radon flux at the surface will be substantially below the public dose limit.

Other uranium projects

There are no other active uranium mines in Australia at present but detailed proposals exist for at least four projects awaiting development approval. There are two potential uranium projects in Western Australia, at Kintyre (1100 km north-east of Perth) and Yelirrie (620 km north-east of Perth). Both of these have been the subject of environmental impact statements but with little further progress. This is due to the policy of the Federal Labour Government which, since 1982, has limited uranium production to three named mines, Nabarlek, Ranger and Olympic Dam. Within the Alligator Rivers Region of the Northern Territory there are two proposed uranium developments, Jabiluka and Koongarra, that both came very close to commencing operations in the early 1980s.

Jabiluka comprises two ore bodies located about 20 km north of the existing Ranger operation. Although explored and developed by Pancontinental Mining, the Jabiluka lease was acquired by ERA, operators of the Ranger mine, during 1991 and the project was renamed North Ranger in 1993. The original proposal was for an underground mine with a mill located nearby at the surface. Tailings were to be cycloned with the coarse fraction, about 50% of the total production, being returned to the underground stopes as backfill after mixing with cement. The remainder of the tailings would be deposited in a conventional ring-dyke structure covering about 180 ha, possibly to be built in three equal stages. The final rehabilitation plan described a multi-layered cover over the tailings dam not less than 3 metres thick and including a 1 metre compacted clay blanket sandwiched between layers of lateritic material. The upper layer would be expected to support vegetation (Pancontinental Mining Ltd, 1979).

At present the mine plan for the development of Ranger North is being re-designed by personnel from Ranger Uranium Mine with completion anticipated in 1994. The mine will still be an underground operation but no processing facility will be built. The plan will call for ore to be processed at the existing Ranger mill, which suggests that the tailings would be deposited on the Ranger site. This could be in a worked-out pit or the tailings dam, but a pit is the more likely choice under the present ERs. The choice of pit would depend on the timing of the operation.

The proposed Koongarra project included tailings disposal in two custom built pits, each about 14 ha in extent. The pits would be about 9–10 metres deep in weathered schist with their bases at least 10 metres above the water table (Fry & Morison, 1982). The pits would be built sequentially allowing design for the second pit to be improved on the basis of lessons learned from the first.

One recent example of tailings disposal activity was the hazard reduction work undertaken in the upper South Alligator valley. It was decided to reduce the radiological and physical hazards to the public associated with the abandoned uranium mines and the various associated processing sites, including the South Alligator mill. The processing sites were characteristically littered with old machinery, mining equipment, abandoned buildings etc whilst the workings included pits, shafts and adits. The radiological hazard arose from contaminated building materials, waste rock and some small quantities of tailings and contaminated sediments from settling ponds. In the absence of any agreed radiological standards it was determined by the relevant authorities that the wastes would be buried in suitably sited trenches. The criteria for 'clean-up' were determined after radiological surveys of the areas involved. The goal of the work was to reduce the external gamma radiation dose rate across each site to an average of $< 0.5\mu G.h^{-1}$ with no single reading greater than $1\mu G.h^{-1}$ (Akber et al, 1992). The burial sites were chosen to be unattractive as campsites and were revegetated using native plant species.

Current practice in other countries

Of all the other uranium producing countries in the world the United States has perhaps the most comprehensively documented procedures for dealing with uranium mill tailings. Many of the regulatory procedures throughout the world draw heavily from the American codes and regulations. Consequently much of the United States regulatory framework is discussed below.

Certainly there is a great deal of work in progress on both abandoned and active uranium mill tailings piles in terms of rehabilitation and containment works. Information from other countries was very variable and was taken from responses from mine operators and regulating authorities in Canada, France, Namibia and Niger.

USA

The deposition of tailings from uranium mills in the USA is governed by the provisions of the Code of Federal Regulations (CFR), specifically 40 CFR Chapters 192 and 264, the Nuclear Regulatory Commission (10 CFR) and local and State mining ordinances and laws. In addition there are orders from the Department of Energy (DoE) which have been applied to many facilities, but not to those which are the specific responsibility of DoE itself. This is scheduled to change by the end of 1993, with the promulgation of a new addition to 40 CFR. The new section, Chapter 834, will deal specifically with the requirements for protecting the public and the environment against radiation including an assessment of risks including ground water pollution risks. The anticipation is that modelling will be an integral part of this process but, as yet, there are no recommended ground water risk assessment models approved. It is understood that several models are being developed.

The major thrust of the regulations in 40 CFR relate to reducing emanations of radon from the tailings, preventing the spread of tailings materials through erosion of the containment structure and preventing contamination of waters by seepage. In the USA radon barriers are usually constructed from clay or similar earth materials. The design is site-specific and based on radon flux as measured on site at the time of the construction works.

All above-ground tailings impoundments are now required to be lined under the provisions of 40 CFR. The liner has to be double-skinned with a seepage collector system located between the two skins. Many operators in the USA consider a seepage *detector* system to be a suitable substitute for a collector system, and the EPA has apparently accepted this line of argument on at least one site in New Mexico. The lower liner may be a compacted clay layer provided that it is not less than 3 feet thick (0.91 metre) and has a vertical permeability of not more than 1 X 10^{-7}cm.sec^{-1} (40 CFR).

The regulations stipulate that all surface impoundments must be located at least 440 yards (402 metres) from any current or potential source of drinking water and operators must be able to show that the design is not going to permit the migration of hazardous constituents into ground waters. Furthermore,

> All surface impoundments must be designed, constructed, maintained and operated to prevent over-topping resulting from normal or abnormal operations; overfilling; wind and wave action; rainfall, run-on; malfunctions of level controllers, alarms and other equipment; and human error.

In 1986 it was proposed that new uranium mill tailings impoundments be limited to a maximum size of 40 acres (16.2 ha) or continuous disposal be practised with no more than 10 acres (about 4 ha) exposed at any one time (Federal Register, 1986). The proposed ruling did not apply to existing impoundments, which were to be allowed to operate until the end of 1992. The proposal suggested that new impoundments be built with compartments of 10 acres. As only one or two impoundment cells would be open at one time, radon emissions would be reduced considerably. All these impoundments would be required to have liners, in accordance with 40 CFR 192, to prevent groundwater contamination. Such a requirement would have tremendous technical and financial implications for the milling facilities concerned. Existing facilities were to be permitted to be used subject to a range of conditions governing the granting of exemptions. These related to:

- circumstances beyond the operator's control preventing the construction of a new impoundment;
- demonstration that the mill is in compliance with all EPA standards, and NRC regulations and licence conditions especially regarding protection of the public.

All exemptions would cease at the end of December 2001 after which time no new tailings may be placed on any existing tailings pile. Licences for new tailings impoundments would be granted under 10 CFR 40 by the NRC.

The approach to the remediation of tailings sites differs depending on the ownership of the site (eg was it ever under Federal Government control or was the product exclusively for US Government use?), and the current operational state of the site. Under US legislation uranium tailings sites are classified as being either inactive, where the tailings date from before 1978, or active. The remediation of inactive sites is being carried out under the auspices of the Uranium Mill Tailings Radiation Control Act (UMTRCA). The group assigned to do the work is known as the Uranium Mill Tailings Remedial Action Project (UMTRA), part of the Department of Energy and based in Albuquerque, New Mexico.

Twenty four inactive sites have been identified. One site is in Pennsylvania and the remainder are in nine western states, and all have been included in the UMTRA program. In addition there are possibly more than 5000 vicinity properties which are likely to require remedial action[2]. All the work is due to be completed by September 1994 although extension through to 1998 is likely due to budget constraints. By December 1992 work at 11 sites had been completed, seven sites were in progress and planning was nearly completed for the remainder.

The standards for the clean-up operation were established by the Environmental Protection Agency (EPA) in 1983 and supplemented by groundwater standards in 1987. The original standards relate to radiological conditions, specifically Radium 226:

(a) The concentration of radium 226 in land averaged over any 100 m^2 shall not exceed the background level by:

 (1) 1.5pCi/g averaged over the first 15 cm of soil below the surface; and

 (2) 2.15pCi/g averaged over 15 cm thick layers of soil more than 15 cm below the surface.

(b) In any occupied or habitable building

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

 (2) the level of gamma radiation shall not exceed the background level by more than 20 microroentgens per hour.

In November 1993 the EPA promulgated a Final Rule relating to 40 CFR 192. In this rule it is stated that the timely emplacement of radon barriers has become mandatory for all abandoned uranium mill tailing sites. The level of radon flux must not exceed $20pCi.m^{-2}$ for a reasonable period of 1000 years and in any event for at least 200 years. The work has to be finished at all abandoned tailings sites by the end of 1997. Also compliance with this standard must be demonstrated by the results of an appropriate monitoring program carried out by the proponent. At the same time as EPA promulgated this new rule, the NRC proposed a rule change in 10 CFR 40 to bring their standards into line with the EPA requirement. Compliance monitoring need only be infrequent once work on the containment has ceased. If work cannot be completed by December 31 1994 then exemptions can be sought and there may be up to two years to comply.

Standards relating to groundwater were added in 1987 and the appropriate section of 40 CFR 192 is as follows:

(c) the concentration of any listed constituent in groundwater as a result of releases from residual radioactive material at any designated processing site shall not exceed the provisions of §§

2 A vicinity property is one which has had uranium mill tailings transported to it either intentionally or by wind and/or water erosion.

264.92 - 264.94 of this chapter as modified by § 1 92.02 (a) (3) (i) and (ii) except that for the purposes of this sub-part:

(1) The Secretary shall carry out a monitoring program adequate to define the extent of ground water contamination by listed constituents from radioactive materials and to monitor compliance with this sub-part.

2) The Secretary may propose and, with the Commission's concurrence, apply alternate concentration limits provided that, after considering practicable corrective actions, the Commission determines that these are as low as reasonably achievable, and § 264.94(b) is satisfied. (This section sets out specific concentration limits for maximum concentrations of groundwater constituents.)

(3) The functions and responsibilities ... with respect to 'facility permits' shall be carried out by the Commission.

(4) The remedial period established under Subpart A may be extended by an amount not to exceed 100 years if:

(i) the concentration limits ... are projected not to be exceeded at the end of this extended remedial period,

(ii) institutional control ... is instituted, as part of the remedial action at the processing site and wherever contamination by listed constituents from residual radioactive materials is found in ground water, or is projected to be found,

(iii) the ground water is not currently and is not now projected to become a source of supply for public drinking water subject to the provisions of the Safe Drinking Water Act during the extended remedial period, and

(iv) the requirements of Subpart A are satisfied within the time frame established under section 112(a) of the Act, or as extended by Act of Congress.

In (4) above the remedial period is defined in the Act as the period of time beginning 7 March 1973 and ending with the completion of requirements specified under a remedial action plan.

It should be noted that ammonium sulphate, the principal constituent of concern (contaminant) in mine waste waters at Nabarlek is not listed as a hazardous chemical in Appendix 8 to this section of 40 CFR.

The Nuclear Regulatory Commission has set down a list of criteria relating to the operation of uranium mills and the disposal of process wastes. In summary, the 13 technical criteria listed in Appendix A to Part 40 of 10 CFR are listed below.

1 Siting to minimise disturbance and dispersion of wastes by natural forces: remote location; tectonic stability; groundwater considerations etc.

2 Avoidance of many small sites; concentrate wastes in as few locations as possible unless it is impractical to relocate wastes.

3 The prime option is a below-grade repository, either in mines or specially excavated pits.

4 Site design details, regardless of containment being above or below ground:

- minimise upstream catchment area;
- wind protection;
- relatively flat slopes, less than 5:1 (h:v) in general but 10:1, or less, is the desirable slope; steeper slopes may be proposed but the compensating factors that make such slopes acceptable are to be clearly identified together with the reasons why shallower slopes are impracticable;
- full, self-sustaining vegetative cover; except in arid zones where such a cover may not be possible;

- a rock 'mulch' cover is to be substituted except where the final cover is greater than 10 metres thick and slopes are less than 10:1 and erosion risk is low, etc.

5 Ground water monitoring to comply with EPA standards of 40 CFR 192; this includes the use of liners, flood protection etc.

6 Earth cover over the site shall last for at least 1000 years in controlling radiological hazards to the extent reasonably achievable and, in any case, for at least 200 years and to limit radon releases to less than levels set in the criterion.

7 Baseline monitoring programs to be undertaken for at least 12 months before operations commence.

8 During milling, airborne emissions must be as low as reasonably achievable.

9 Financial security to be established prior to commencement of operations to ensure that rehabilitation and decontamination costs are covered.

10 A minimum charge of (1978) US $250 000 to cover costs of long term surveillance to be deposited before termination of operations.

11 Site and by-product ownership issues; includes transfer of land essential to ensure the long term stability of the site to either the US or a State government at no charge other than administrative and legal charges.

12 Long term site surveillance at least annually by the government agency responsible for the site; reports to be made within 60 days of the inspection. NRC may require more frequent inspections.

13 Secondary groundwater protection standards as set down in Criterion 5 are concentration limits for specific constituents. This criterion includes an extensive list of other constituents which must be considered, including gross alpha activity. The list is drawn from 40 CFR 192 but is not to be considered exhaustive; other individual constituents may be added on a case by case basis.

These regulations cover 12 pages of text in the CFR and the list of contaminants covers a further five pages and consequently have not been reproduced here.

Canada

In 1982 it was estimated that there were at least 130 million tonnes of uranium tailings in Canada. These were at many sites throughout the country and covered a total area of approximately 10 km^2 (Hamel & Howieson, 1982). By 1991 the quantity had increased to 165 million tonnes and it is estimated that the total will exceed 230 million tonnes by 2000 (Uranium Institute, 1991). In the early 1950s tailings were mostly deposited as slurries, usually into natural depressions (muskeg fill depressions) or valley/dam type locations at sites in the Athabasca Basin including the Eldorado, Muskeg and Gunnar minesites (Saskatchewan Environment and Public Safety, 1991). There has also been some discharging of tailings into deep lakes particularly in the Lake Elliot region. This had apparently been done in the past in the remote northern part of the country at a number of small sites (Ritcey, 1989). The theory behind such a method is that there would be no free oxygen to assist reactions in the tailings, which would in turn reduce the rate at which radionuclides might pass into solution. Also human and animal access would be unlikely. The long term prognosis is that natural sediment will be deposited over the tailings and provide a cover which would reduce the opportunities for re-suspension and solution of the tailings and associated constituents.

In recent times the Atomic Energy Control Board of Canada (AECB) has tended to regard tailings impoundments as 'storage areas' rather than 'containment and disposal' sites. This is because there is a very high probability of glaciation returning to Canada within 15 000 years, ie within the half life of some of the radioactive contaminants. Also the waste still contains 85% of the original radioactivity and AECB considers that in future it may become necessary to reduce the level of radioactivity or isolate the material until the radioactivity has decayed to a low level that will not impact on the environment.

Consequently, all uranium tailings repositories must now be designed to be near impermeable with a permeability of no more than 10^{-6}cm.sec^{-1}, with a comprehensive network of monitoring wells to check that there is no seepage. There has also been work on using barium chloride to precipitate dissolved radium with a view to preventing its dispersal. Flocculants are apparently needed to speed up settling times and reduce the risk of contaminated water escaping from ponds.

The Cluff Lake mine is located in Saskatchewan and is a combination of both open cut and underground workings producing about 125 000 tonnes of ore annually of which 118 844 tonnes were mill feed in 1992. The uranium is extracted by an acid leach process and tailings are neutralised with milk of lime and deposited sub-aerially as a slurry with approximately 45% solids. Discharge spigots are located at the perimeter of the containment and relocated monthly. The containment is a valley fill site with seepage control by means of a bentonite cut-off. The in-situ dry density of the tailings is 1.25. The structure has a design life of 20 years and a modelled structural life of 500 years.

IAEA (1992) reported that at Rabbit Lake, Canada, a pit with fractured sides is being used to contain uranium mill tailings. By the end of 1992 some 2.7 million tonnes of tailings had been deposited (Federal Environmental Assessment Review Office, 1993). The pit has been underdrained by construction of a drift, approximately 210 metres long, 6 metres above the base of the pit which descends at a gradient of 5% to a sump. A shaft was sunk from the surface to meet the sump and dewatering pumps were installed at the sump. At the base of the pit a 6 metre layer of random waste rock was placed followed by a 6 metre layer of graded rock and then a 1.5 metre filter layer of sand to trap fines during tailings placement. The sand and rock filter layers are continued around the perimeter of the pit, being built up the walls as tailings are deposited. This layer ensures drainage of all waters, groundwater seepage, pore water and surface runoff as well as aiding consolidation of the tailings. Once the containment is topped out this drainage layer will offer a preferential flow path for ground water so that the tailings are by-passed (Clark, 1989; Federal Environmental Assessment Review Office, 1993). In a proposal for a similar repository in the Deilmann pit at Key Lake the final tailings cover proposed by the mine operator, Cameco, is a 1.5 metre layer of sand, which will then be covered by up to 15 metres of water (Chadwick, 1994). Environment Canada stated that they would prefer use of a waste rock cover although the Atomic Energy Control Board stated that the plan fulfilled requirements for a conceptual decommissioning plan. The Environmental Assessment Panel concluded that the options proposed for decommissioning the Rabbit Lake pit were viable but further data collection and modelling were needed to enable a final decommissioning plan to be developed (Federal Environmental Assessment Review Office, 1993).

All water collected from the drainage sump is returned to the mill for treatment, ie the operation is similar to that at Bessines in France. When this pit is full the cap will divert infiltration and runoff to the edges of the pit where it is hoped the water will run preferentially into the fractured zone and so away from the tailings. This should significantly reduce the risk of contaminant transfer from the tailings.

France

It has been estimated that in 1992 there were nearly 50 million tonnes of uranium mill tailings in France (Daroussin & Pfiffelman, 1993). Within France the remediation of uranium mill tailings is controlled by a regional authority *Direction Regionale de l'Industrie, de la Recherce et de L'Environnement* (DRIRE - Regional Directorate for Industry, Research and the Environment). The radiological aspects of environment protection, especially protection of the public, are dealt with in a decree, No. 90–222 dated 1990, which takes into account the French mining code, directives from Euratom and ICRP principles. The cut-off for defining uranium material is 0.03% uranium by weight (compared to the level of 0.02% defined in the legislation governing activities in the Alligator Rivers Region and the Australian Code of Practice on the Mining and Milling of Radioactive Ores; in Canada the definition is >0.05% uranium by weight; and at Jackpile-Laguna in New Mexico, USA, the definition of ore set down by the regulating authorities is >0.06% U_3O_8).

At the Bessines facility the 'dry' method of tailings management and deposition is practised. Originally tailings were deposited behind a simple dyke which was also a settling pond, and consequently the tailings were left partly water covered. Since 1987 the system has changed and neutralised tailings are deposited at a remote location as described below.

Tailings are handled at a moisture content of about 20%. In the first stage the coarse fraction, sand, is separated and used as a fill material; the residue is dewatered to about 20% moisture content using a pressure filter and placed in temporary storage; the water is recycled in the plant. Trucks are used to move the tailings 4 km to an abandoned mine pit. The base of the pit contains a coarse rock filter and water drains from the tailings, via the filter, into underground workings beneath the pit. Water is pumped from the workings then treated with barium chloride and basic polychlorosulphate of aluminium to remove radionuclides, and flocculants to remove suspended matter, before being discharged to a water course. Some tailings have been used to backfill stopes in the mine and coarse cycloned fractions were used to build the dykes for temporary tailings impoundment in the early stages of operation.

The Bessines facility is to be decommissioned during 1994 with total rehabilitation scheduled to be completed by the year 2000. This will mark the end of uranium processing in France as all future demands will be met by imported, cheaper, yellowcake. The tailings repository will be covered with a 1 metre thick layer of partly compacted waste rock before being allowed to revegetate either naturally or by hydroseeding; there will be no tailings left exposed.

There is also a report that elsewhere in France tailings have been placed in a repository in the centre of a waste rock pile which was itself then covered with 'several metres' of earth and rock (P. Bruneton, pers comm).

Sweden

This is another country where dry management is practised. Tailings are dewatered to about 17% moisture content then trucked to a containment facility. Once at the site tailings are placed in layers and compacted to achieve a permeability of $10^{-7} m.s^{-1}$. As a consequence of the compaction process radon emanations are kept low and the risk of settlement is minimised (IAEA, 1992).

Russia

There were no replies to enquiries sent to Russia. It is understood that there are a number of uranium mines in both the former USSR and elsewhere in Eastern Europe where very large tailings and heap leach piles are being abandoned. The rehabilitation program for these sites is unknown at present.

Gabon

No information was received in response to requests sent to uranium mine operators in Gabon.

Namibia

The world's fourth largest uranium mine is located at Rössing in Namibia. The mine produces about 7 million tonnes of tailings annually. The metallurgical process is an acid leach and tailings are not neutralised before being deposited. The approximately 35% (by weight) slurry is pumped from the mill over distances varying from 750 metres to 4.5 km, to be deposited sub-aerially in a single repository. Deposition points are located around the perimeter of the containment and are used sequentially with frequent relocation to even out the beach formation. The tailings are not subjected to any additional chemical or physical treatments and settled densities of 2.1 $t.m^{-3}$ are reported by the mining company. This density is higher than the usual range of values and is attributed to the combination of the lack of neutralisation and the coarseness of the grind. Also the value provided was not an in-situ dry density figure.

The tailings impoundment covers an area of 600 ha and is an upstream valley fill with a 200 years design life that is reasonably expected to last 1000 years. Seepage collector systems around the perimeter of the containment intercept seepage both above and below ground. Seepage is pumped back to the dam or returned to the milling circuit depending on origin and metal content. There is also a comprehensive solution-recycle system associated with the tailings disposal operation to maximise efficiency of water use. Dusting from the beaches has been arrested on inactive areas by placing a final cover layer of coarse tailings which are not subject to wind blow. The final cover proposed for the tailings is a multi-layer design incorporating a radon barrier (C. Johnson, pers comm).

Niger

The Arlit mine, operated by Societe Mines de l'Air, is an open cut operation mining 2.5 million tonnes of ore and waste rock annually (1992 figures). The tailings totalled 800 000 tonnes of which 300 000 tonnes were solids. Tailings are deposited un-neutralised in a sub-aerial manner with the main spigot located centrally but relocated around the central area periodically. The tailings repository is an above ground tailings dam which has a PVC geomembrane to prevent seepage. The settled density of tailings is quoted by the operators as being 2.0 tonnes /cubic metre, again this is unlikely to be a dry bulk density figure. The tailings are filtered prior to deposition. There is no revegetation program because of the desert climate and no final containment or cover designs have yet been defined. There is no re-use of tailings.

South Africa

There was no response to the questionnaire sent to South African contacts and the literature search revealed a relatively low level of detail. Production of uranium in South Africa began in 1945 and peaked in about 1980. Considerable effort was put into reprocessing gold tailings to extract associated uranium mineralisation. It has been estimated that the total volume of these gold/uranium tailings was about 2.3 billion tonnes with an annual production rate of tailings of 102 million tonnes (Robertson et al, 1987). These efforts were concentrated at East Rand, Klerksdorp and Welkom. In 1982 a uranium mine was opened at Beisa. From 1952 until 1991 a total of 167 000 tons of U_3O_8 was produced at 35 locations throughout the country (Ford, 1992). Uranium is still produced as a by-product of the gold industry as well as from the copper tailings from the Palabora Mining Company's concentrator.

Disposal methods are generally low cost solutions. The paddock method uses upstream construction techniques to provide an outer ring of 'day' cells and an inner 'night' basin. Tailings are deposited into either the inner or outer section at the appropriate time of day. Surplus water is decanted to a separate water recycling dam. The outer walls are kept semi saturated and allowed to consolidate for use in the next construction phase. This method is apparently very cost effective although the rate of increasing wall heights is relatively slow, being controlled by the settling and evaporation rates. There was no information provided about rehabilitation plans or standards.

Summary of current practice in uranium mill tailings disposal

The overall common objective internationally is to contain the tailings for a very long time and this is usually achieved in one of three ways. These are disposal in:

- a mine pit;
- underground workings; or
- an above ground containment.

Also the risks to human and environmental health are to be reduced to levels that are as low as reasonably achievable.

The major concern for human health in the short term is excessive exposure to radon and its progeny. Generally this issue is addressed by means of placing thick earth and/or rock covers over repositories. Other options make use of multi-layer covers incorporating clay barriers as in the USA, or water as in some Canadian sites. In these ways public exposure can be kept below approved limits. Over time, other risks become significant, eg ground water contamination by heavy metals or salts, relocation of long-lived radionuclides and their possible ingestion, and direct gamma radiation. This last item can be a concern with respect to buildings constructed over or near uranium mill tailings repositories. The option of keeping tailings saturated is not considered suitable by authorities because of the problems of geotechnical instability and ease of erosion from the containment. A further concern is the possibility of differential settlement occuring as the tailings dry out which could result in disruption and failure of containment structures. Also the presence of excess moisture in a tailings mass may aid leaching of contaminants. Finally the settled density of tailings is reduced if they are kept saturated and this reduces the amount of tailings that can be stored in a given volume of containment.

In many instances the placing of tailings in mined-out pits, where they are available, has been seen as the most economic and secure way of achieving these objectives. This is being used in Canada, France and Australia. Deep burial in underground mine workings has also been proposed to reduce risks to the population and the environment. The concept of in-pit disposal is discussed in detail in the following section.

Methods of disposal

The only three significant options for uranium mill tailings disposal worldwide are:

- placement in-pit;
- placement in underground mine workings; and
- above-grade structures.

The in-pit disposal option

In-pit disposal of tailings is an option that has many attractions from an environmental protection point of view. If a suitable pit is available within a reasonable distance from the mill this option may be very economical. If an in-pit repository is being considered there are a number of factors and characteristics of the pit that must be taken into account.

Ideally the tailings will go into a pit which has already been mined out (eg Nabarlek, Australia, Spook, USA and Rabbit Lake, Canada), or else a temporary storage facility will be needed until such time as the pit is available (eg Ranger, Australia). There have been cases of tailings placement in operating pits and Sehmel (1978) has shown a schematic example. The method resembles strip mining in as much as the mine face advances with waste being used to raise a dyke behind the operations. This dyke, together with the far wall of the excavation, forms an impoundment in which the tailings are deposited. The impoundment could be lined with compacted clay or grouted if required to reduce seepage. A major issue in such an operation would be to ensure that workers were not over-exposed to radon by virtue of working in a pit that was also a tailings repository. It is debatable if the expense of constructing a containment within a pit, such as the Spook site, is economically justifiable.

If the overburden to ore ratio is very low the pit may not have sufficient volume to hold all the saturated tailings after processing. This arises because ore has a density of about 2.6 t m^{-3} whereas tailings tend to have settled densities in the range 1.1 to 1.3 t m^{-3}. Such a situation would require the construction of an additional tailings storage facility which could be another pit, a ring-dyke around the rim of the existing pit, or a separate tailings dam.

If the tailings mass in the pit is saturated complete rehabilitation may not be possible due to geotechnical problems associated with settlement of tailings with time. For example, differential settlement of tailings after a cover has been constructed could lead to structural failure of radon barriers etc. In order to maximise settlement as soon as possible the tailings should be as dry as possible, not saturated. The placement of wicks/vertical drains or the employment of consolidation techniques are two options that should be examined in these circumstances. The placing of vertical wicks in the pit-deposited tailings at the Nabarlek mine has apparently been successful in speeding up initial settlement of tailings (P. Bailey, pers comm).

Tailings placed below groundwater table level may pose a threat to the environment; this would be exacerbated if the pit were water-filled above the tailings. This can be overcome by preparation of the pit, eg lining or grouting the sides to prevent ground water flow in and out of the tailings mass and/or the pit (Ritcey, 1989). An alternative would be placement of a high permeability zone around the deposited tailings to offer a preferential seepage path and discourage mixing of the groundwater with tailings water (IAEA, 1992).

Tailings in a pit will generally be buried deeper than in other forms of repository, apart from those returned to underground workings. In this way the potential for erosion, and consequent dispersal of the contaminants, is considerably reduced.

Other advantages of the in-pit option are:

- the completed site is likely to be aesthetically more pleasing than an above ground facility;
- airborne transport of contaminants is unlikely to be a concern;
- the deeper the pit the smaller the exposed surface area of the tailings and the less the amount of cover and rehabilitation work required;
- there is effectively no risk of the wall of the containment failing when compared to a ring-dyke system.

If the pit has to be lined or a permeable layer installed, flatter side slopes might be needed to facilitate the lining process. Steep slopes are less costly to cover but they increase the installation problems and the risk of liner failure. A wider, shallower pit would have serious financial implications on the initial mining operation. A liner may be subject to settlement or rupture as a consequence of differential settlement in the tailings and/or the cover materials.

The use of a pit as a tailings repository may preclude, or at least complicate, future mining operations in the vicinity. If there are zones of ore grade material remaining in the pit it is unlikely that they could be safely or successfully mined in the event of changes in economic circumstances.

At Nabarlek in Australia the tailings were returned to the pit from where the original ore had been mined with no special preparation of the pit before deposition took place. The initial deposition was carried out sub-aqueously in a pit that has been described as being dry, ie there was no significant inflow of groundwater. Later the deposition method was changed to sub-aerial. The later history has been previously described.

In the case of other pits where tailings might be deposited a major question has been the need for lining of the pit and/or drainage of the floor and walls to permit removal of potentially contaminated waters to a safe disposal facility rather than allow them to disperse to the environment; underdrainage would also improve settled density of tailings and help to reduce settlement times and risk of problems arising from subsidence of the tailings mass after capping.

The IAEA and USEPA both favour the use of liners where pits are to be used for tailings impoundments. They also require that tailings are deposited, at least 7 metres above the water table. In an extremely arid zone this could be achieved by placing tailings in the upper portion of a pit (Sehmel, 1978). The most suitable environment in which to use a mined-out pit is an arid one where evaporation exceeds precipitation and groundwater is deep. The US authorities still consider that, even under these conditions, pit lining is necessary. High rainfall areas are considered unsuitable if the wet season causes the water table to reach the surface, thus increasing the risk of contamination being spread into the environment (IAEA, 1992).

At Spook in Wyoming USA, although the cell in the base of the pit was 5 metres above the ground water table, the floor of the cell was lined with a leachate reduction layer about 1 metre thick. Also the containment cell had a 3 metre thick granular layer placed around the top and sides outside the final cover. The purpose of this layer was to encourage drainage around the containment and further reduce the risks of water infiltrating the pile and leaching out contaminants. By these means the risks of contaminating groundwater were reduced considerably (Morrison-Knudsen, 1988).

However, whilst the in-pit option is seen as very suitable for many reasons, not all authorities have always been convinced that it is the ideal solution. It is interesting to note that the EPA in the United States has not been keen on this practice in the past due to concerns over potential risks of groundwater degradation and dispersal of contaminants into the environment.

In 1991 an inquiry was begun by the governments of Canada and Saskatchewan to review uranium mine developments in northern Saskatchewan. Amongst the proposals under review was placement of tailings from the McClean Lake and Mid West Joint Venture proposed mines into the JEB mined-out pit. This proposal was based on the system used at Rabbit Lake. The inquiry determined that this in-pit 'pervious surround' style of containment was not yet adequately tested and that the project proposal would be suspended for five years to allow a better evaluation to be made of the performance of the Rabbit Lake system (Joint Federal-Provincial Panel on uranium mining developments in northern Saskatchewan, 1993). Another, later, report by the Federal Environmental Assessment Review Office (1993) concluded that the tailings disposal system at Rabbit Lake was the most appropriate for that situation and that the scheme is functioning as predicted. However, the panel recommended that a detailed monitoring and assessment program to be set up by Cameco, the mine operating company and defined seven tasks to be included in such a program. The seven tasks were to:

- assess whether the properties of the tailings are consistent with those used when the facility was designed;
- calibrate and update predictive models on contaminant transport in the receiving environment using data from field testing of the B-zone tailings, Rabbit Lake tailings, Rabbit Lake waste rock and B-zone waste rock;
- determine the appropriate tailings' properties, including permeability and porosity, by field testing;
- determine the permeability and relevant hydraulic properties of all surrounding rock units by field testing;
- determine the quality of pore water in order to estimate the quality of water that may reach the receiving environment;

If the water cover option were to be selected for decommissioning the pit:

- predict the long-term quality of surface water and surrounding groundwater using three-dimensional flow or geochemical models;
- maintain a detailed inventory of the chemical and physical characteristics of tailings deposited in the facility.

One outcome of this program will be field data that can be used to validate models used to predict the long term performance of the facility. Two other concerns expressed by the panel about the efficient operation of the facility were the formation of ice lenses within the tailings mass and segregation of the tailings during deposition. The first concern is that thawing ice lenses could force pore water out of the tailings mass and cause contamination of groundwater. The second concern is because desegregated tailings are of heterogeneous permeability. The coarse tailings separate out on the upstream side of the beach whilst the fines form areas of low permeability at the downstream edge. These low permeability areas may retain pore water for longer periods of time than the remainder of the tailings and this water could freeze giving rise to a mass of frozen tailings and in turn leading to the first concern. Cameco have indicated that subaqueous deposition or deep snow cover would both provide sufficient insulation to reduce freezing of tailings. The company also indicated that the desegregation of tailings can be managed by using a high solids content in the tailings slurry, rotating discharge points frequently and keeping beach lengths short.

The underground mine disposal option

The use of mine tailings as backfill in underground mines was first recorded from South Africa in the early 1900s (Down & Stocks, 1977). Modern technology is developing ways of placing complete tailings back into stopes rather than just the coarse fractions (Engineering & Mining Journal, December 1993, p59). At the BBU Bleiberg/Kreuth lead-zinc mine in Austria high density backfilling using whole tailings was introduced in 1990. This became necessary when the further disposal of fine tailings in surface ponds was not permitted. The high density slurry pumped at Bleiberg is 80% < 0.16 mm in size and stopes up to 1000 m^3 are filled in one continuous operation. The actual fill material disposes of all the tailings. It contains a maximum of 5% by weight of cement and is pumped as 76% solids and a specific gravity (SG) of 2.1 in a fully automated system. Use of tailings in this way is a preferred option where the tailings may be considered inert, but in the case of un-neutralised uranium tailings from an acid leach process this is not so. Concerns relate to the potential for contamination of groundwater. Backfilling of uranium mines using tailings was carried out extensively in the Grants mineral belt in New Mexico, initially to facilitate the mining of previously abandoned adjacent stopes but more recently as a preferred tailings disposal option (Thomson & Heggen, 1982).

In the proposed Jabiluka (now renamed North Ranger) uranium mine in Australia plans involved the separation of the coarse tailings fraction, using a cyclone, and then return of this material, mixed with cement, as a backfill in the underground stopes. It is estimated that only about 50-60% of the tailings could be returned to the workings in this manner. This is due to the proportion of tailings that would be too fine to separate economically (the slimes); the decrease in bulk density of the backfill material by comparison with the original rock; and the probability that the cyclone would be recovering about 70% of the tailings for about 70% of the time (WLPU, 1981).

If uranium mill tailings are to be used as backfill there are a number of other considerations that need to be taken into account.

- Emanations of radon and radon daughters will continue from the tailings. If there are other areas of the workings that are active, the mine ventilation system will have to be capable of dealing with these increased gas levels.
- Most of the radioactive components in tailings are contained in the fine fraction, and so the radioactivity of tailings slimes disposed of above ground will not be significantly reduced.
- An above-ground facility is still needed to dispose of the slimes.
- The separation of slimes creates a waste that requires special handling, as they are virtually impossible to consolidate and remain highly susceptible to erosion.
- Placing of tailings underground may lead to groundwater contamination, especially if the tailings are un-neutralised and the mine rock is highly fractured.
- The cost of relocating tailings is high.

The above-ground disposal option

In terms of numbers of sites, as well as total volume, most of the world's uranium mill tailings are contained above ground, ie above the natural land surface. The primary objective for their disposal is to physically contain the wastes, and the various types of impoundments used have been listed previously in this review. The above-ground option is usually the least-cost option, as mine pits are not usually available during the mining phase of development. Also tailings dams have often been engineered simply as tailings containments rather than as water retaining structures which are more costly.

Commonly, valley dam impoundments have been used as these represent one of the cheapest ways to contain tailings. However, the site must be reasonably close to the mine, have suitable hydrological characteristics, and be large enough to contain all the tailings from the proposed operation. Once filling is completed the surface and walls of the impoundment have to be covered to reduce radon and radiation emanations to appropriate levels as well as providing erosion protection and dust containment.

Where the topography cannot provide a suitable site, ring dyke or turkey's nest impoundments may be used. These comprise a single, self-closing embankment, usually on more or less level ground. Whilst these structures can be any shape, rectangular and circular are the commonest forms used. The embankments may be built as water retaining structures with zoned construction and rolled clay cores, or more simply by using tailings themselves to provide a structure that will retain the tailings slurry. In the latter case the coarse fraction of the tailings may be cycloned off for this purpose, leaving the fines and slimes to be placed in evaporation ponds. The base of the containment needs to be relatively impermeable to minimise seepage and it may be necessary to construct a floor of compacted material to achieve this or consider use of a synthetic liner. The structures in the past were often single, massive cells, but current design regulations in the USA impose a maximum cell size. Again, once milling has ended, the tailings containment will have to be covered with a layer, or layers, of suitable material to reduce radiation and radon emissions to appropriate levels and to prevent erosion.

Both these above ground options have the disadvantage that the long term containment of the tailings is in doubt as all above-ground structures are subject to erosive forces. Thus the risk of failure of above-ground repositories is inherently greater than for those facilities where tailings disposal is in pits or underground.

The main advantages and disadvantages of each option are summarised in Table 1.

Revegetation and covers

Where tailings disposal works result in an above ground structure there will often need to be some form of revegetation. This is usually either to blend the structure into the landscape and assist with erosion protection or to prepare the site for some further form of land use. The final requirements for revegetation and covers over tailings are usually site specific. Certainly there is great variation throughout the world in terms of design requirements, vegetation and climatic types and site characteristics. Revegetation is commonly required in most mine rehabilitation schemes. With respect to revegetation of uranium mill tailings there is little published information. In some instances in the past, revegetation was a matter of simply seeding or planting directly into tailings. Also covers of earth or bitumen have been applied in some locations, mostly as dust control measures with little specific effort to limit radon emanations or encourage plant growth. Such simple practices are no longer acceptable, the need to cover the tailings is usually related to one or more of the following aims:

- prevention of water ingress and reduction of subsequent leaching out of contaminants;

Disposal option	Advantages	Disadvantages
Above ground	Can operate simultaneously with mining. May be cheap to establish if tailings used in construction. Valley fill sites may have low construction costs. Whole tailings can be contained. Tailings pond can also function as evaporation pond to assist in mine waste water management. Most widely used. Tailings easily available to be re-worked if required.	May be regarded as only temporary by authorities and tailings may have to be relocated to mine pit etc at end of mine life. May require construction of associated structures to minimise risk of environmental impact in the case of failure or to contain and/or treat seepage. Seepage control essential. Expensive if built as a water retaining structure. Post close out settlement may take a long time and lengthen period before company can be released from responsibility. May need maintenance for a long time. Long term risk of tailings spill, increasing as structure weathers and erodes. Increases land area impacted upon by mining. Airborne and waterborne dispersal of contaminants possible following erosion etc.
In mine, below ground	Very long term containment possible. Unlikely ever to require maintenance. Can possibly incorporate whole tailings. Can be operated simultaneously with mining. Airborne dispersal of contaminants effectively impossible. Structural failure of impoundment virtually impossible.	Slimes may need to be contained separately. Needs suitable groundwater conditions. Mine waste water management system needs to be able to cope with evaporation requirements. Tailings not available for re-working.
In pit (also includes custom-built below ground repositories)	Very long term containment possible. Unlikely ever to require maintenance. Whole tailings can be contained. Pit preparation costs unlikely to be as high as above ground options. Considered "prime option" by the IAEA. Airborne dispersal of contaminants effectively impossible. Structural failure of impoundment virtually impossible.	May need pervious-surround work to minimise ground water contamination possibilities. Construction cost of impermeable containment could be high if suitable pit not available. Not normally possible to operate simultaneously with mining at the same location. Requires a suitable pit to be available pre-mining or a "Nabarlek-style" situation. May involve double handling of tailings eg as presently required in Environmental Requirements at Ranger Uranium Mine. Re-working of tailings difficult to arrange as deposits will be deep by comparison with above ground tailings dams.

Table 1

- limiting access to tailings materials for people and animals;
- control of radon emanations;
- control of dust;
- reduction of erosion to prolong containment.

The prevention of erosion may be achieved by the promotion of vegetative covers or construction of physical erosion barriers. These barriers may be achieved through landform design in terms of slope length and angle. This last decision is usually dependant on the climate at the site; sites in areas of heavy rainfall will require erosion control measures different to those found in arid zones. Also the final land use proposed for a site will dictate the type of cover and revegetation program that is required. Schemes required to return land to agricultural production or recreational facilities will have very different requirements to areas being returned to wilderness parks, for example.

At Ranger the goal and objectives for rehabilitation have been agreed between the Northern Territory and Commonwealth Governments (OSS, 1992). The broad goal is to establish an environment in the Ranger project area that reflects, to the maximum extent that can be reasonably achieved, the environment of adjacent areas of Kakadu National Park. The major objective relates to the revegetation of the site in a manner that will result in a match with the surrounding areas of Kakadu National Park and enable park management to be the same as for surrounding areas. Thus the present expectation is that an open Eucalyptus forest community will be established over the rehabilitated area. The depth of waste rock material over any buried tailings is likely to be such that it is not thought likely that tree roots will penetrate to any contaminated material, provided that the rate of erosion is no greater than in the natural state.

In the case of Nabarlek the proposal is that a cover of waste rock will be built over the pit and contained tailings and contaminated wastes from the mill site. Original plans included a radon/water infiltration limiting barrier to be included as a layer within this cover. However, the need for this barrier has recently been re-examined and a new design which has no separate radon barrier has been adopted. Technical meetings have agreed that radon flux through the new design will be below required limits and that groundwater pollution will not be exacerbated as a consequence of rainwater infiltrating the cover. The cover will be revegetated with local native species to match the surrounding area as much as possible, in accordance with the wishes of the traditional land owners.

At Rum Jungle the final landforms were revegetated with a range of grasses, particularly on their flatter tops and gentler sideslopes. The intention was that these relatively shallow-rooted plants would improve the erosion resistance of the land surface. The relatively steep sides of the re-modelled waste rock dumps were given a cover of rip-rap as erosion protection. The old tailings disposal area is relatively flat and is a low erosion risk as a consequence. Elsewhere management practices include the removal of trees from rehabilitated areas before they become established. This is because it is feared that tree roots could penetrate the clay layer within the covers and permit infiltration of surface water which in turn could lead to premature failure of the containment structures. On the waste rock heaps such a failure would result in increased aeration of the pyritic spoil with consequent release of acid rock drainage that would have a severe impact on the downstream environment. The tailings were all placed in the Dyson's open cut and covered with soil and rock materials. It is not anticipated that the tailings would be exposed or liable to disperse from the containment in the normal course of events.

In the USA revegetation of uranium tailings containments is a variable requirement. UMTRA staff do not generally favour revegetation at sites, citing concerns that tree and shrub roots might penetrate the layers of the cover structure and cause premature failure; they are equally concerned that the vegetation itself might encourage colonisation by fauna, both macro and micro, whose burrowing might again breach the integrity of the cover layers and so reduce the life of the containment. This last view was a concern expressed by site staff at Gas Hills, Wyoming, where the area surrounding the containment is being considered as a future recreation reserve and wildlife refuge. At the Conoco site near Falls City, Texas, the final landforms are being grassed with no tree planting. Finally, many of the sites are in areas where climatic conditions would make the successful establishment of any vegetation very difficult.

Concern has been expressed from time to time that burrowing animals may breach the cover and lift tailings to the surface. This has been observed in Australia with monitor lizards as the agent (P. Waggitt, pers obsvn) and in North America with rabbits and woodchucks (Robertson et al, 1987). It is also possible that animal burrows could become foci of erosion that would threaten the integrity of the whole cover and containment. The action taken to reduce this risk is usually to construct a multi-layer cover containing cobble-size rocks as one of the lower layers as well as the use of rock riprap over the whole structure (UMTRA, 1985, Caldwell & Reith, 1993). However, it has also been reported that placing rock as the final cover layer increases the weed, shrub and forb cover at the expense of grasses (Beedlow and Carlisle, 1984, Caldwell & Reith 1993). One solution offered to the problem of root penetration was to include a slow release herbicide as a layer below the cobbles. However, the chemical was estimated to have a life span of between 100 and 200 years at most, and was therefore neither desirable nor sustainable and has not been implemented (UMTRA, 1985).

In areas where the establishment of vegetation is likely to be successful, the use of vegetated covers has some advantages. The evapo-transpiration of the vegetation is effective in removing water from the cover layers and reducing water percolating through the structure; also surface drainage requirements and the dusting hazard are reduced (Caldwell and Reith, 1993). If the vegetation is native then its maintenance is likely to be minimal or zero. It should also be noted that use of other options such as rip-rap or rock mulch covers may not provide solutions that are socially acceptable. This is because such procedures can effectively alienate the land from any immediate or future beneficial land use. This is in contrast to programs to establish either wilderness or any improved land use.

Post close-out monitoring

Once the repository has been closed out consideration has to be given to the monitoring program required to enable continued assurance to be given that there is no unacceptable or unexpected environmental impact arising from the tailings. The main considerations are:

- what is an appropriate monitoring regime;
- who will carry out the work; and
- who will pay the associated costs?

It is often the case that the mining company will have this responsibility, at least until such time as the regulating authorities are prepared to agree that the site has been rehabilitated to an acceptable standard. The assumption is then that the regulators will have to adopt the role of monitors, but by what means and for how long is often unclear. In the USA the monitoring is paid for by the mining company's 'security deposit' of (1978 dollars) $250 000 and the work is carried out by a federal regulatory agency. In Australia this question has not yet been fully addressed in the case of the uranium mines of the ARR.

The style of monitoring program traditionally envisaged involves sampling of groundwater bores at agreed intervals. In Canada, Intera Kenting Limited (1992) carried out a study for the Atomic Energy Control Board to establish if remote sensing techniques could usefully be applied in this area. The motivation was the significant expense incurred when operating traditional monitoring programs based on sample collection. The study looked at a range of remote sensing applications using both satellite and aircraft as platforms. The final recommendation was that annual surveys using Landsat Thematic Mapper data be used as the basis for monitoring programs at uranium mill tailings disposal sites. The criteria that could be used in such a monitoring program include:

- vegetation — encroachment, moisture stress, die-back;
- moisture — drainage patterns, seepage expression, ponding;
- soils and rock — dam failure, erosion, channel siltation, soil condition, pit or heap morphology change;
- radioactivity — uranium levels in the environment.

The baseline situation should be established using thermal infrared and multispectral imagery. If the situation is found to be changing rapidly then more frequent airborne surveys are recommended. The recommended method of storing and using the data is a geographic information system (GIS). The report suggests use of personal computer-based systems and indicates that costs would be substantially reduced by comparison with ground based programs (Intera Kenting Ltd, 1992). The use of GIS for this purpose is a possible topic for future development at the Office of the Supervising Scientist.

Remote sensing methodology of other types may also have potential for use in this area. For example airborne electro-magnetic surveys can be used to study sub-surface distribution of saline waters. Use of this technique is already being investigated by the Power and Water Authority of the Northern Territory of Australia (D. Pidsley, pers comm). This work could possibly be applied to studies of seepage plumes from tailings containments. Airborne radar and low level videography are further examples of remote sensing techniques which could be applied to problems of environmental monitoring and impact assessment, and whose usefulness should be investigated (Riley et al, 1994).

Conclusion

There have been many different approaches taken around the world in addressing the problems of uranium mill tailings disposal. These changes have occurred over time as a result of improved understanding of the public health risks, as well as the growing concern that the natural environment should be protected and its degradation reduced to the minimum possible, whilst still achieving sustainable development. Disposal choices are often site specific, relating to options available, eg is there a suitable pit within reasonable distance; does the local topography offer a suitable disposal site; what was the method of deposition of the tailings? Even the chemistry of the extraction process may influence the choice of tailings disposal method. Overall the most pressing concern is to ensure that the contaminated materials stay contained for as long as possible in order to reduce the environmental and health risks as much as possible. Legislation exists in many countries but it has proved to be very difficult to obtain detailed information from offshore sources and little, if any, of the legislation of other countries is apparently held in Australian libraries.

Application to the Alligator Rivers Region

The solution to the question of what is best practicable technology (BPT) for uranium mill tailings disposal in the Alligator Rivers Region (ARR) may vary from site to site. The environment would seem to be best protected by returning the tailings to a below-ground location where long term containment is easier to achieve and groundwater contamination is either not an issue or can be kept below what are determined to be acceptable limits. Such a location is regarded by the US Nuclear Regulatory Commission as the 'prime option' (10 CFR part 40). However, in considering this option one must recall the reservations implied by the Canadian authorities in their decision to wait for a further five years of data from the pervious surround system being used at Rabbit Lake before approving a similar plan at Mid West Joint Venture. This should be seen as an opportunity to evaluate the effectiveness of that specific system and not a rejection, albeit even temporary, of the concept of in-pit disposal.

In the Alligator Rivers Region the in-pit solution has been regarded as the better option. Under the existing Environmental Requirements (ERs), the two mines in the ARR are required to place tailings in worked out pits. The ERs were drawn up after the Ranger Uranium Environmental Inquiry, where the Fox Commission which sat for the Inquiry, did not share the mining company's confidence that tailings could be simply and safely stabilised *in situ*. In particular, the Commission was unconvinced that revegetation of tailings could ever be successfully achieved, although it did concede that there might be significant advances in revegetation technology in the future (Fox et al, 1977).

The ERs are site specific. In the case of Nabarlek, ER 26 states that:

(a) All tailings shall, as soon as practicable, be dealt with by being deposited in or transferred to the mine pit in a manner approved by the Supervising Authority.

(b) No tailings shall be deposited or transferred to the pit before the pit is prepared in a manner designed to minimise seepage and approved by the Supervising Authority.

As has been described elsewhere, the Nabarlek tailings have been placed in the pit and will be covered in accordance with the Decommissioning Plan agreed by the Supervising Authorities. Thus the ER is being complied with.

At Ranger the situation is different because there was no suitable pit available for tailings disposal when milling began. The relevant ER 29 reads:

(a) Subject to paragraph (b) of this clause, all tailings shall be dealt with by being deposited in or transferred to the mine pits in a manner approved by the Supervising Authority not later than five (5) years after the cessation of mining (whether under this Authority or otherwise in accordance with the law) on the Ranger lease.

(b) If after 10 years from the date of issue of the Authority but before the cessation of mining on the Ranger Project Area, the Supervising Scientist reports that he is satisfied that, by dealing with the tailings in the manner outlined in the report, the environment will be no less well protected than by depositing or transferring the tailings to the mine pits and, following the receipt of such report, the Minister for Environment, Housing and Community Development, the Council and the Joint Venturers agree that the tailings should be dealt with in the manner outlined in the report, all tailings shall be dealt with in the manner outlined in the report.

The Council referred to in section (b) above is the Northern Land Council.

At present the tailings from the Ranger operation are deposited in an above-ground turkey nest dam and ER 29(a) requires that this 1 km^2 structure and all the contained tailings be relocated into worked-out mine pits when mining ceases. This operation would be very costly. The mining company has indicated that it is carrying out a program of research to determine if the option of rehabilitating the tailings dam and contents *in-situ* could be demonstrated to the Supervising Authorities to leave the environment 'no less well protected' as required in ER 29(b). Outcomes from this program would be the subject of the report referred to in ER 29(b). In addition the report would need to prove that an *in-situ* rehabilitation program was best practicable technology. There is no published timetable for the production of this report at the present time. When, and if, an application is made by the mining company to rehabilitate the tailings *in-situ*, the proposal will be evaluated taking into account many of the issues discussed in this review, as well as any further information that may have become available by that time.

The major outcomes of this review follow.

- No single country has yet come up with all the answers to the questions that arise from disposal of uranium mill tailings.
- The issues, problems and range of solutions faced by the authorities in the Alligator Rivers Region are the same as those faced by uranium miners and supervising authorities elsewhere.
- The preferred solution would seem to be to place tailings in a mined-out pit, if a suitable pit is available.
- The rehabilitation standards to be employed at a site are likely to be more appropriate if they are developed site specifically, as proposed for Australia, rather than generic standards applied without variation as is apparently the case in the USA.
- The present system and approach taken in Australia are no less demanding than that found anywhere else and may be more demanding than most other countries. This is particularly true in respect of revegetation requirements in the Alligator Rivers Region.
- The review has shown that there is not a great deal of new information to be gleaned from outside Australia in terms of these issues.

There would appear to be few countries making regulations or creating standards in relation to uranium mill tailings disposal. Apart from the work in train in Australia the USA, France and Canada are the only countries which have accessible comprehensive legislation. There are, however, several countries which have borrowed part of the legislation from the USA to provide a basic code of practice for local use.

The present approach taken by the Australian authorities would seem to be correct. By comparison with other worldwide practices, they appear to be in the leading group in terms of environmental protection effort. Certainly the work being done on landform design is at the forefront of technology (Willgoose & Riley, 1994). The mining companies of the ARR have been amongst the leaders in developing technology for tailings disposal. Also research in the ARR by mining companies and the Environmental Research Institute of the Supervising Scientist (ERISS) on techniques to establish native vegetation is apparently leading the world. It is quite possible that these programs will have worldwide applications when they are completed. Certainly resolution of the debate on the final repository for the Ranger tailings could well shape opinions and practice around the world.

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Appendix A

Definition of Best Practicable Technology

In order to ensure that the risk of environmental detriment as a consequence of uranium mining within the Alligator Rivers Region is minimised the Commonwealth of Australia requires that operations are carried out under the provisions of the Environmental Requirements (ERs). The ERs were drawn up at the commencement of mining and have been incorporated into the Northern Territory Act which is used to control uranium mining, the Uranium Mining (Environment Control) Act of 1979. The ERs appear as Schedules 1 and 2 to the Act for the Nabarlek and Ranger mines respectively.

The same definition of 'best practicable technology' applies to both projects:

Nabarlek Environmental Requirement 41 and Ranger Environmental Requirement 44

'Best practicable technology' is that technology from time to time relevant to the Nabarlek/Ranger Project which produces the minimum environmental pollution and degradation that can be reasonably achieved having regard to:

(a) the level of effluent control achieved, and the extent to which environmental pollution and degradation are prevented, in mining and milling operations in the uranium industry anywhere in the world;

(b) the total cost of the application or adoption of that technology relative to the environmental protection to be achieved by its application or adoption;

(c) evidence of detriment, or lack of detriment, to the environment after the commencement of the Nabarlek/Ranger Project;

(d) the physical location of the Nabarlek/Ranger Project;

(e) the age of equipment and facilities in use on the Nabarlek/Ranger Project and their relative effectiveness in reducing environmental pollution and degradation; and

(f) social factors including possible adverse social effects of introducing new technology.

Supervising Scientist for the Alligator Rivers Region

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