

DEPARTMENT OF COMMUNITY SERVICES AND HEALTH

# Australian Radiation Laboratory



Radiation Protection in the Mining and Milling of  
Radioactive Ores

Volume 2

Lecture Notes from a course conducted at  
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TABLE 1WASTES GENERATED FROM MINING AND MILLING RADIOACTIVE ORESMINE WASTES

- . Solid:
  - waste rock, below ore grade uranium material (bogum)
  - miscellaneous waste
  
- . Liquid:
  - run-off from the RRZ
  - mine drainage
  - seepage
  - waste rock pile run-off
  - miscellaneous waste
  
- . Airborne:
  - radon and radon daughters
  - ore dust
  - waste rock dust

MILL WASTES

- . Solid:
  - tailings
  - precipitates, concentrates
  - miscellaneous waste
  
- . Liquid:
  - run-off from the RRZ
  - process liquids (solvents, etc.)
  - tailings liquid
  - tailings seepage
  - ore stockpile run-off and seepage
  - miscellaneous waste
  
- . Airborne:
  - radon and radon daughters
  - dusts (yellowcake, tailings, ore)
  - other gaseous emissions

Typical of the milling process is the following description of the acid leach process (Pidgeon 1985).

The main steps taken during the acid leach process are:

- (1) Crushing and grinding - reducing the rock to fine sand and greatly increasing the effective surface area available for reaction.
- (2) Preconcentration - upgrading of ore concentrate using flotation techniques for physical properties of minerals. While these are not widely used, they are sometimes effective eg. for ore where the uranium is contained in heavy minerals.
- (3) Leaching - uranium is taken into solution in sulphuric acid. It is necessary in cases where a part of the uranium is present in ore minerals in the +4 state to add an oxidant to enhance dissolution in sulphuric acid. Main oxidants used are manganese dioxide and sodium chlorate, hydrogen peroxide and air. Ferric ion is important in 'catalysing' the oxidation reaction.
- (4) Solid-liquid separation - requiring washing and separation using filtration and/or settling and decantation techniques. Organic flocculants are generally added at this stage to improve settling rates of solids.
- (5) Uranium recovery from solution - either of two processes is generally employed at this stage; ion exchange or organic solvent extraction generally using a tertiary amine and long chain alcohol dissolved in kerosene as extractant. Two steps are involved in each technique.
  - (a) the 'pregnant' liquor is brought into contact with the organic extractant phase and uranium is transferred to that reagent leaving other elements in the solution
  - (b) uranium is then removed from the extract phase using a stripping reagent eg. a nitrate, sulphate or chloride solution.
- (6) Precipitation of uranium - generally uranium is precipitated with ammonia, although environmental considerations have prompted a search for substitutes.

The US NRC Environmental Impact Statement, (NRC 1980) described the characteristics of operation of a model acid leach mill treating sandstone ore of an average grade of 0.10%  $U_3O_8$ . The reagents added during the process are estimated in table 2 below.

TABLE 2  
Additives for Acid-Leach Process  
(from NRC 1980)

<u>Additives</u>	<u>Quantities,</u> <u>kg/t ore</u>
Sulphuric acid	45.0
Sodium chlorate	1.4
Ammonia	1.1
Flocculant	0.06
Amine (long chain)	0.015
Alcohol	0.04
Kerosene	0.45
Iron (rods for grinding)	0.35

Note that except for the addition of sulphuric acid there is little else in the table that can be considered hazardous in the long-term as ammonia and organics will decompose or volatilise, sodium chlorate is reduced to sodium chloride and iron addition is not significant. However, where pyrolusite ( $MnO_2$ ) is used as an oxidant, manganese is introduced as a potential 'long-term' contaminant.

The waste stream from the uranium removal contains the residual finely ground rock particles, the solvent (acid or alkali), the oxidant, ammonia, organic reagents, precipitates, and any chemicals added to condition the stream to a suitable chemical state for long term impoundment and disposal (such as precipitation of radium and neutralisation).

This stream of wastes, usually mixed with and transported in suspension in water, is termed the tailings.

Potential contaminants in the tailings are shown in table 3.

TABLE 4

## SOME POTENTIAL CONTAMINANTS IN LIQUID WASTES

Contaminant	Mine Drainage		Decant Solution and Tailings Seepage		Decommissioned Mine Drainage	
	Acid	Basic	Acid	Alkaline	Acid	Basic
<u>Radioactive</u>						
$^{226}\text{Ra}$	+	+	+	+	+	+
$^{222}\text{Rn}$	+	+	+	+	+	+
$^{210}\text{Pb}$	+	+	+	+	+	
$^{230-232}\text{Th}$	+		+	+	+	
$^{210}\text{Po}$	+		+		+	
$^{235-238}\text{U}$	+	+	+	+	+	+
<u>Non-Radioactive</u>						
$\text{H}_2\text{SO}_4$	+	+			+	
$\text{HCO}_3$		+	+	+		+
$\text{CO}_3$		+	+	+		+
$\text{NH}_3$	+	+	+			
Cl		+	+	+		+
$\text{SO}_4$	+	+	+	+	+	+
PO	+		+		+	
F	+		+	+	+	
$\text{NO}_2$	+	+	+	+		
Na	+	+	+	+	+	+
Fe	+		+		+	
Mn	+		+			
Co	+		+		+	
Ni	+		+		+	
Zn	+		+		+	
Cu	+		+		+	
Pb		+				
V	+		+	+	+	
Cr	+	+	+			
As	+		+		+	
Mo	+	+	+	+	+	+
Se	+	+	+	+	+	+
Ba			+			
Ca	+	+	+	+	+	+
Mg	+	+	+	+	+	+
Kerosene )						
alcohol )						
amine - TBP )						
Oil (lubrication or fuel)	+	+				

### THE WASTE MANAGEMENT PROGRAM

The wastes produced as a consequence of mining and milling of radioactive ores, unless properly managed and treated, will constitute a continuing source of environmental pollution and radiation exposure. As well as radioactive wastes, non-radioactive wastes, particularly heavy metals and salts, are damaging to the environment.

The life of a mining and milling operation can be considered as progressing through three time stages:

- . the operational phase;
- . a transition phase, where some institutional controls are retained; and
- . the long-term, where wastes are to be suitably contained without the need for intervention by man.

To achieve the objectives of (a) radiation protection (b) minimisation of releases to the environment (c) final disposal with minimum need for human intervention (d) retention of maximum land use potential and (e) minimisation of the area of permanent disturbance, a waste management plan must be developed during the feasibility and planning phases of the project. Some aspects of this plan will be considered during the preparation of an Environmental Impact Statement. An EIS would normally be required for any proposal to mine or mill uranium.

The plan must identify all wastes; characterise the wastes to enable assessment of the potential for release of contaminants, utilise appropriate and develop applicable technologies, obtain sufficient data on the surrounding environment for assessment of impact, identify critical group(s) of members of the public and take into account the expected and predictable long-term processes on the sites to ensure long-term integrity of wastes.

The final design of a waste management system arising from the plan should be expected to withstand predictable processes over the long-term and ideally utilise the environmental processes to enhance the integrity.

Central concepts to the waste management program are:

- (a) the restricted release zone, in which the waste management processes take place

- (b) the use of best practicable technology, requiring a discussion of how the adopted waste management scheme satisfied criterion;
- (c) storage and disposal, which indicates the intention or not for retrieval;
- (d) decommissioning and rehabilitation, mutually dependent terms describing the measures to prepare for the long-term, these requirements are an integral part of a waste management program and
- (e) the long-term, following full stabilisation and rehabilitation of the site when natural systems are relied upon to control the release rates of contaminants from the disposed wastes.

The development of a waste management plan will, because of the many areas of potential impact, be a product of a multi-discipline team. Each discipline, through competent representatives, will bring into the process its own values, attitudes and prejudices. This should give a richness and variety to the considerations which are required for the development and adoption of the final plan. Such a multi-discipline team approach should ensure that the plan fulfils a multi-purpose function and satisfies all the real concerns.

The development of a waste management plan is an iterative procedure. It involves a series of decisions by management following consideration of options and assessment of suitability both economically (does the plan affect the economic suitability of the project?), and regulatory (is the appropriate authority satisfied with the plan?). An indication of the procedure required to be followed is shown in figure 1.

The major steps are data collection and evaluation; development of an appropriate waste management system including operation and maintenance procedures, and, approval by the appropriate authority including any public consultation.

#### Data Collection and Evaluation

This phase commences at the time of first prospecting, exploration and identification of an orebody. The information gained to enable decisions to be made whether to progress to later stages is the initial input into the development of a waste management plan.

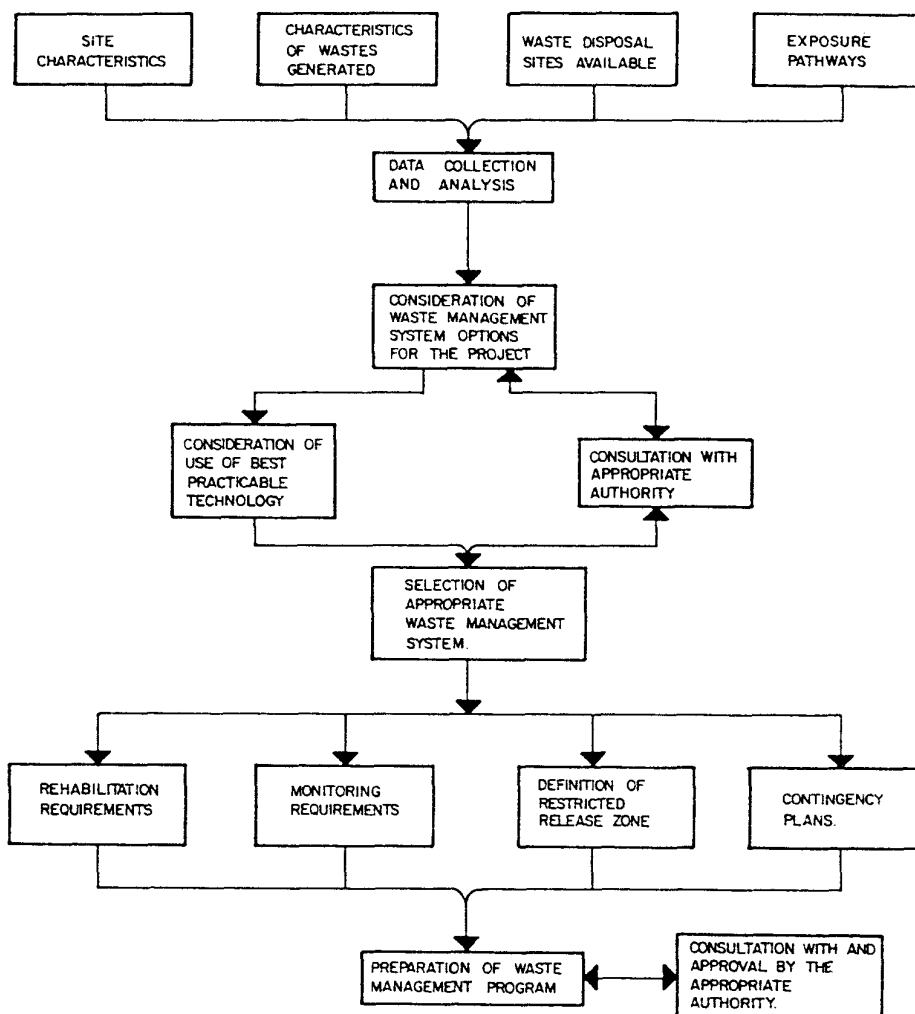


Figure 1. Development of an approved waste management program.

In order to develop a program it will be necessary to determine the natural conditions pertaining at the site, e.g., climate, topography, geology, hydrology, soils, biota and the existing radiation environment. This should be evaluated in conjunction with the proposed project information, e.g., type, size and location of ore body(s), mining methods, milling methods, waste generation, etc. From these evaluations an overall project plan will develop. This includes the waste management programme together with the monitoring programme, contingency programmes to deal with unplanned events and programmes for decommissioning and rehabilitation.

The four major interdependent factors that need to be considered in developing a waste management program are the environmental characteristics of the project area and its surrounds, wastes expected to be generated; the waste disposal sites available, and the pathways of exposure of human and other biota to contaminants.

Environmental characteristics considered should include: geography and land use; climate; demography; biota; hydrology; geology; mineralogy; hydrogeology; soils; existing radiation environment; and archaeological, anthropological, historical and aesthetic aspects. This information should be presented in detailed reports, summary maps, catalogues, inventories etc. to enable a balanced appreciation of environmental factors affecting the site and setting. This information should be as complete as possible, using historical records where available, should show diversity of species, interrelationships, and should incorporate statistical analysis of the data to provide information about the possible errors in the data and variability within or of the system.

Wastes Generated by the Uranium Mining and Milling Operation have been discussed previously. The volumes and characteristics of the wastes expected to be generated by the project must be delineated. These will include solid wastes, liquid waste and airborne waste.

Solid waste from mining may be used, depending on the mineralogy, radioactivity and chemical reactivity, for various construction projects on the site. Such uses include the construction of roads, embankments, diversion structures and other fill.

The below ore grade uranium material and waste rock are often a most significant source of  $^{222}\text{Rn}$  gas on the project. Mill tailings and decant liquor precipitate,  $(\text{BaRa})\text{SO}_4$ , are a solid waste contained in liquid. Tailings are generally unsuitable for further use without conditioning when it may be utilised to fill mine workings or as an embankment construction material.

Liquid waste may arise from mine drainage which comes in contact with the ore body, seepage or run off from waste rock dumps and may contain dissolved uranium, radium, thorium, radon, thoron, heavy metals and be quite acidic (or basic).

Airborne waste consists of oredust, containing radionuclides such as  $^{226}\text{Ra}$ , or  $^{220}\text{Rn}$ . Other airborne wastes consist of products of combustion, fugitive emissions from the milling process and dusts containing radioactive decay products in the packaging area.

The information should identify all types and sources of waste from the mine and mill. The estimated quantities, concentrations, physical and chemical characteristics should be specified along with the anticipated average and maximum rates of production. This should contain the mine plan, the milling flow diagram, and details of any recycle systems.

The waste disposal sites available are usually close to the mine and the mill because of the large volumes of tailings and waste rock which are generated. The engineered disposal facilities must cope with circumstances at the nearest suitable site. The environmental characteristics of the site together with the mineralogy of the ore and the mining/milling methods adopted will largely determine the type of waste disposal system employed. Detailed information, on the site investigations and engineering designs for the disposal site options considered will be required.

The pathways of exposure of humans and other biota to contaminants must be identified and detailed. These pathways can include atmospheric and aquatic modes of release. The information should identify the major pathways and describe the likely impact on critical groups of humans and biota, including bio-accumulation processes. This should include assessments of background (pre project) levels and pathways.

#### The Waste Management Program

Following assessment of all the relevant information and the taking of the required decisions a waste management program detailing in full the procedures to be adopted to manage all materials of the project including those won on site, those imported onto site and those made on site from exploration to measures suited for long-term rehabilitation. This program comprises the waste management system, together with monitoring programs, contingency plans and decommissioning and rehabilitation plans. The program must contain procedures for regular review and update.

The programme would contain statements of the objectives of the project, location and lease arrangements, the existing environment, proposed mining and milling operation (including resource aspects) and the anticipated environmental impacts of the project.

The waste management system would include statements of: the restricted release zone(s); the water management plan and the management of mill wastes.

The monitoring programs include statements of the physical networks, procedures (including frequency) and resource allocation for assessing the impacts of the wastes. The programs should identify interactions with other agencies carrying out related monitoring and the procedures for exchange of information.

Contingency plans should involve risk analysis of unplanned events and evaluation of the associated effects. The plan should allow for emergency resources and procedures and for contingency monitoring. It should provide for immediate ameliorative action and for a reporting procedure to the appropriate authority and other responsible persons.

The decommissioning and rehabilitation program should provide strategies and surety arrangement to provide for completion of the program. The plan should include measures: for progressive rehabilitation; for control of radon flux; to reduce the external gamma radiation exposure at the surface; to control wind and water erosion of the rehabilitated waste disposal site(s); to revegetate the waste disposal sites; for restricting access of humans and fauna; and, for post operational monitoring and surveillance to establish the performance and success, or otherwise, of the rehabilitation programme prior to termination of responsibility.

The waste management programme must include a suitably detailed operations and maintenance manual to ensure that all aspects of the programme are understood and followed by the persons responsible for its operation.

The foregoing sections have discussed the institutional arrangements applying to the management of radioactive wastes from the mining and milling of radioactive ores. The technical aspects can be considered under the four facets contained in the waste management programme.

The foregoing sections have discussed the institutional arrangements applying to the management of radioactive wastes from the mining and milling of radioactive ores. The technical aspects can be considered under the four facets contained in the waste management plan, consisting of:

- . water management systems
- . waste rock and ore stockpile management
- . tailings impoundment
- . decommissioning and rehabilitation.

These are discussed in the following sections.

#### WATER MANAGEMENT SYSTEM

Water is one of the major factors in the design of a uranium mine and mill. In controlled quantities it is a resource as it is the medium in which the extraction and concentration of uranium takes place and it is also a convenient medium for transporting large quantities of wastes. In uncontrolled quantities water has the potential to increase the volumes of waste to unmanageable proportions.

Water quantity and quality are the factors which require constant management to ensure the efficient operation of the mine and mill; and, the minimum impact on the environment through the aquatic pathway.

The availability of water at a project is the result of many influences but it should be noted that in Australia variability and unpredictability are the factors which characterise the hydrologic cycle. This affects the measures necessary for a water management system which is capable of dealing with all contingencies.

It is not possible to develop a generic water management system for Australia because not only is there temporal variability but also significant differences in climate associated with location. These differences are large over relatively small distances.

#### Restricted Release Zone

Central to the development of a water management system is the restricted release zone. This zone is a space in which materials are handled and the waste management processes take place.

Wastes may not be discharged from a restricted release zone without appropriate controls and discharge limits approved by the appropriate authority.

The restricted release zone usually includes the minepit, haul roads to it and other areas, ore stockpiles and reactive waste rock heaps, crusher and ore storage areas mill site, tailings impoundment areas, seepage collector sump, tailings pipeline corridor and sumps and ponds to which the above areas drain.

Within the restricted release zone all waters are to be collected, stored and distributed or used in accordance with an approved water management system.

#### Water Management System

The water function of the management system is to provide water for the operation of the mine and the mill manage waters inside the project area to ensure that the risk of seepage and release of water containing waste is minimised using best practical technology and to ensure that surplus waters which come into contact with the operations are minimised and disposed of without detriment to the environment outside the restricted release zone.

Sources of waste water include excess process water from the milling operation which is retained within and accompanies the tailings as a transport medium, collected mine pit run off and seepage, collected underground mine seepage, run off from ore stockpile, chemical storage, waste dump, borrow area, undisturbed area, paved area and pipeline corridor, excess water within evaporation ponds and water from bores and dams.

These waters may vary in chemical composition, concentration of suspended solids and degree of intermixing with each other.

Waste and make-up water can be used as a source of mill process water, water for dust control, cooling water for power supply, water to transport tailings materials to tailings impoundments and water to cover deposited tailings for minimisation of radon flux where required.

The volume of water within storages can be reduced by evaporation, evapotranspiration, discharges from restricted release zones, infiltration and seepage to deep aquifers, and enhanced evaporation.

There are various classifications of water management systems, based on the conditions under which releases may be made from the restricted release zone. These are:

Absolute no release, in which all waters are held for evaporation and there is no release of water to the environment including seepage

No release, with no intentional or inadvertent release outside the restricted release zone seepage, must be minimised by the use of best practical technology

Contingency no release, where waters are held for evaporation except under contingency conditions such as low probability rainfall events

Controlled release, where waters are released under suitable conditions

Uncontrolled release, allowing free discharge with or without treatment.

Acceptable forms of water management system usually include only the no release, contingency no release and controlled release systems. However, a project water management plan may include each type or combinations of them as components of the overall system.

The system should aim at segregation of waters as far as possible to ensure the minimisation of waste bearing waters.

Should a system be classified as contingency no release, controlled release or uncontrolled release the releases will need to meet discharge criteria and standards. These must be formulated to prevent adverse impact on the environment. The establishment of such criteria and standards depends on the use and potential uses of the receiving waters. Aquatic habitat requires more stringent limits on concentration and total load than does for example drinking water or drainage.

The design of the water management system is constrained by many project specific factors including:

- . environmental and legislative
- . project specific
- . site specific
- . system specific factors.

Information should include data on the following:

- . the nature of the project
- . topography
- . geology
- . climate
- . hydrology
- . groundwater
- . water quality criteria and release standards.

This data should be analysed to optimise the water management system. This includes the analysis and synthesis of rainfall and evaporation data and modelling of catchment responses to design events. The analysis should consider the probabilities of occurrence of various events and should also consider the impact of extreme events.

#### Water Balance Design

The design of a water management system is a lengthy process affected by the values, judgements and concerns of the designers, mining companies and appropriate authorities.

It generally consists of:

- . the adoption of a type of water management system, making assumptions about the sizing of structures, pipes, pumps and impoundments
- . determining the relevant factors from the mining and milling plan
- . carrying out sensitivity analyses based on a range of simulated events. The calculations indicate areas for refinement and the process is repeated until an optimum system evolves. This process is shown in Figure 2.

For development of the system the calculations are carried out on a coarse scale for feasibility studies and the time scale for the steps is reduced as the progressive refinements are made.

The water balance calculations depend on many independent variables, the number of which increase markedly with the complexity of the system. The variables can be linear or non-linear requiring complex modelling and

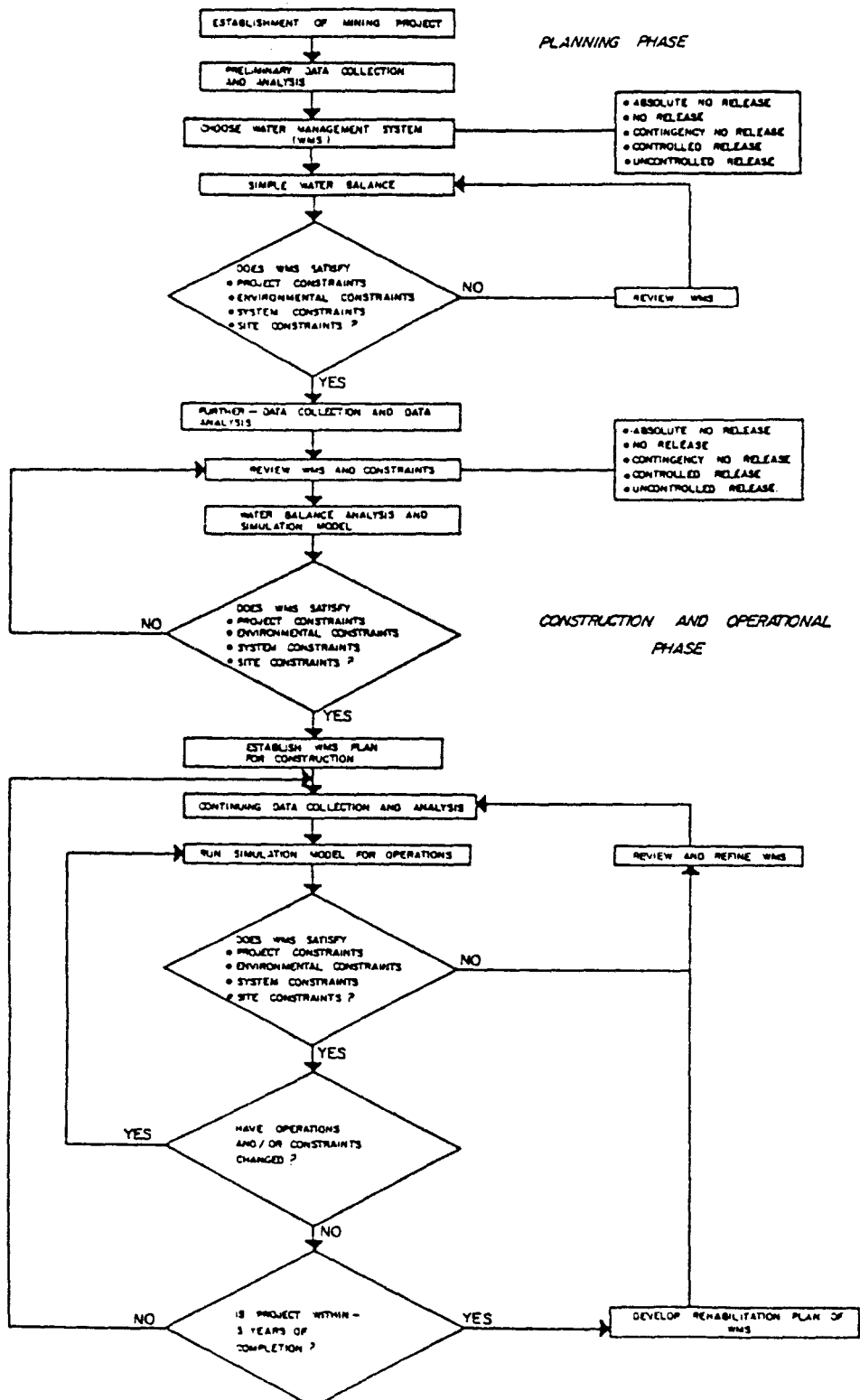


Figure 2. Flow chart for establishment of water management system for uranium mining and milling operation.

analysis. Data to be considered includes:

- . climate, i.e. rainfall, evaporation, lake to pan factors, rainfall intensity - duration curves, and extreme event determinations;
- . catchment, i.e. run-off coefficients, infiltration and storage parameters for soils, area slope and drainage characteristics of catchments;
- . project, i.e. mining rate, stockpile programme, milling rate, tailings production rate, project component duration, tailings characteristics to calculate entrapment, road watering capacity, pumping requirements, mill requirements for fresh water and recirculation, segregation and use of tailings;
- . pond, i.e. volume - reduced level - area curves, estimates of seepage loss, and freeboard; and
- . water quality, i.e. restrictions on the release of waters, requirements for segregation of waters of various qualities, and requirements with respect to contingency releases of water.

#### Documentation and Construction

On completion and approval of a water management plan the structures included in the scheme are to be documented and constructed to take into account the design requirements and the special features of the site. Often the structures are not built at the one time at the onset of the project but are progressively developed in accordance with planned staging dependent on the growth of the mine and waste disposal areas. These structures must take into account the soil characteristics and transmissivity of the underlying strata.

The water in the management scheme becomes a valuable asset both for its value to the project and the potential impact of waters on the environment. This requires design and construction of structures using best engineering practice. Construction requires close attention to sources of materials, foundation conditions, quality control during construction, and monitoring. Construction activities, if uncontrolled, have the potential to change catchment characteristics within the restricted release zone and to change the sensitivity of the water management system.

### Operation, Maintenance and Monitoring

If the water management system, when constructed, is not operated as designed it will be inefficient and could lead to failures. In order to minimise operator error the system should be designed to use passive controls where possible. The intervention of an operator should be required only to effect the necessary transfers to achieve water quality segregation and tailings storage and to correct significant departures from the desired level of freewater in the system.

To achieve efficient operation a detailed manual should set out objectives and procedures including monitoring and simulation to predict future performance. The manual should also contain details of reporting requirements for changes to the system, infringements of requirements and breaches of the restricted release zone.

Once a water management scheme is operational the performance should be monitored and the model calibrated. This should allow for refinements of the coefficients used for the calculations during design and so lead to refinements to the operation of the system to enable objectives to be achieved. In this regard it should be noted that in some aspects the total volume of water accumulated in the system can be very sensitive to some of the coefficients adopted and measures must be taken to use early adjustments to the system.

During the operation all structures must be inspected and maintained to ensure their continued satisfactory operation. With the potential for uncontrolled inadvertent release from the restricted release zone should a structure fail it is important to ensure that inspection schedules are incorporated into the daily operational requirements for shift workers at the plant.

Monitoring should include, in addition to the daily meteorological information, pond levels, ground water quality, level and piezometric pressure, and integrated daily pump transfer volumes for each pump.

Following completion of the project the water management scheme must be closed down progressively. The water required for mill operations must be disposed of without detriment to the environment and all structures decommissioned and rehabilitated to lines and levels which minimise erosion and sediments from the stabilised areas. This should be designed and contained in a decommissioning and rehabilitation plan.

## TAILINGS IMPOUNDMENT

### Site Specific Factors

In general the factors prevailing at an individual mine and mill site will not be the same as those which prevail at another site and the adoption of appropriate procedures will be determined by the assessment of all the factors, the proposal of a scheme which is then checked to ensure that best practicable technology is followed. This evaluation means that best practicable technology is project specific and that the solutions adopted as best practicable technology for one project are not necessarily best practicable technology for another project. For tailings impoundment and rehabilitation each project offers specific advantages and has associated specific disadvantages. The best practicable technology for rehabilitation could be the optimum solution where the specific advantages work in favour of the long term containment of the tailings and the engineering design accounts for the specific disadvantages during the operation (short term) life of the impoundment.

### Factors Affecting Tailings Impoundments

The major factors affecting the design, construction, operation and subsequent rehabilitation of a tailings impoundment include selection of the impoundment site, the type of impoundment, the impoundment dam structure, the control of seepage, the control of radon exhalation, the control of gamma ray emission, the tailings management system, the rehabilitation and revegetation options, and the consideration of geochemical options incorporating site characteristics and geochemical engineering design.

### Design for Rehabilitation of an Uranium Tailings Impoundment

#### Objectives, Criteria and Means

The objectives for rehabilitation of uranium tailings impoundment are based on the following criteria:

- . Protection of man and the environment from the detrimental effects of the radiation contained in the tailings; this includes the chronic as well as the acute effects. The choice of plant process, the use of positive stable containment, adequate cover, minimisation of rates of seepage and the allowance for long term erosion and geomorphological influences is seen as the means by which this objective can be achieved.

- . Protection of man and the environment from the non radiological detriments of the tailings such as the contained chemicals, the products of weathering and leaching by bio-chemical means. The means of achieving this objective are similar to those of the previous objective but include deliberate measures to control the long term bio-chemical regime, notably the minimisation of the exchange of water and oxygen.
  
- . Provision of an aesthetically acceptable decommissioned impoundment. This will usually involve the filling of pits, the design of slopes, drainage patterns, revegetation etc. so that the tailings disposal site "should be returned to conditions reasonably near those of the surrounding environment".

The basic factor behind these objectives is the need to account for not only the short term effects but the long-term effects associated with the rehabilitated impoundment without active management.

#### Site Specific Design

The rehabilitation of a tailings impoundment site does not commence at the completion of milling, when tailings are not longer being produced, but with the selection of the impoundment site and the tailings management system. These must offer a maximum of site specific advantages and a minimum of disadvantages. The disadvantages must be designed for by providing features such as liners and cover caps.

- The selection of the impoundment site should consider factors such as climate, (including annual rainfall patterns, storm intensities, evaporation patterns, wind, geology, topography, ground water regime, association with areas (and potential areas) of population and areas of environmental concern etc.).
  
- The mill process can be designed in a manner which, as well as achieving economic recoveries of uranium from the ore, will ensure the waste products are conditioned to control the availability of contaminants and the location of the contaminants of greater concern.
  
- The type of impoundment to be used is an important consideration which is often dependent on the site selection, geology, topography, climate, the type of mining process to be used (open cut, underground mining, in-situ leaching) and the tailings management system.

### Impoundment Types

The types of impoundments which can be considered are valley dam, ring dyke, mine pit, specially dug pit and underground mine impoundments. The selection of the impoundment type has impacts on the ultimate cost of the projects in terms of money and impact on the environment.

Impoundments on the surface will generally use dams of earth or earth and rockfill construction which must satisfy all functional requirements, ensure integrity under any foreseeable conditions, last indefinitely with little or no maintenance, minimise seepage through the structure and its foundations and minimise the emission of radiation and exhalation of radon gas. The dam must be designed and constructed to conservative criteria. Such criteria do not permit the use of mill tailings as the downstream structural shells.

### Control of Seepage

The control of seepage from an impoundment is dependent on the selection of a site which has ideally low permeability strata below and surrounding the impoundment, long seepage paths to the environment, and low driving heads for moisture. As the purpose of controlling seepage is to minimise the rate of movement of radioactive and heavy metal contaminants so the effect on the environment is minimised it is desirable that the seepage be through strata with strong retarding capacities. If a site can only be selected which is surrounded by high permeability strata then liners, which effectively seal these strata, are indicated. Clay-soil liners compacted under controlled conditions usually meet these criteria in the long term.

Grouting of fractured rock and the use of seepage collection systems assist in the minimisation of total seepage.

### Methods of Tailings Management

The method of tailings management is dependent on the many factors such as climate, water management and the means of controlling radon exhalation. The controlled management of the tailings is one of the major impacts on the capacity for rehabilitation and emphasis should be given to the distribution of the tailings to minimise segregation, to give uniform rates of filling, to maximise the tailings densities and shear strengths, to reduce the potential for long term and differential settlements and to reduce the hydraulic gradients available for seepage. A well designed and controlled tailings management system will improve the ability to successfully stabilise and rehabilitate the tailings.

Methods of tailings management include:

- Saturated (transported, placed and maintained saturated).
- Wet (transported and placed saturated where the tailings form a beach which leads to a pond).
- Semi-Dry (tailings are thickened and transported with a high solids content, discharged sequentially onto drained beaches, where pore moisture is reduced by bleeding and evaporation).
- Dry (moisture is reduced in the mill process by filtering or evaporation and tailings are transported and compacted in a similar manner to earthfill).

The amount of consolidation of tailings, and the consequent settlement which will affect rehabilitation measures is dependent on the initial density, degree of entrapped waters and drainage characteristics of the tailings. Wet management ensures segregation and a high degree of entrapment leading to lengthy periods of large consolidation. Saturated management ensures less segregation but entraps large volumes. Semi dry and dry management ensure that most consolidation occurs prior to placement of cover structures, these methods also promote greater shear strengths which enable more positive measures for placement of cover caps.

The provision of cover caps for the long-term minimises water percolation into rehabilitated impoundments and is the controlling measure on the hydraulic performance of the impoundment in the long-term. Measures which could be considered include impoundment structures which provide drainage for pore water and active management of seepage during the operational phase rather than the impervious zones presently employed.

Figures 3 to 7 show a range of options for tailings impoundment.

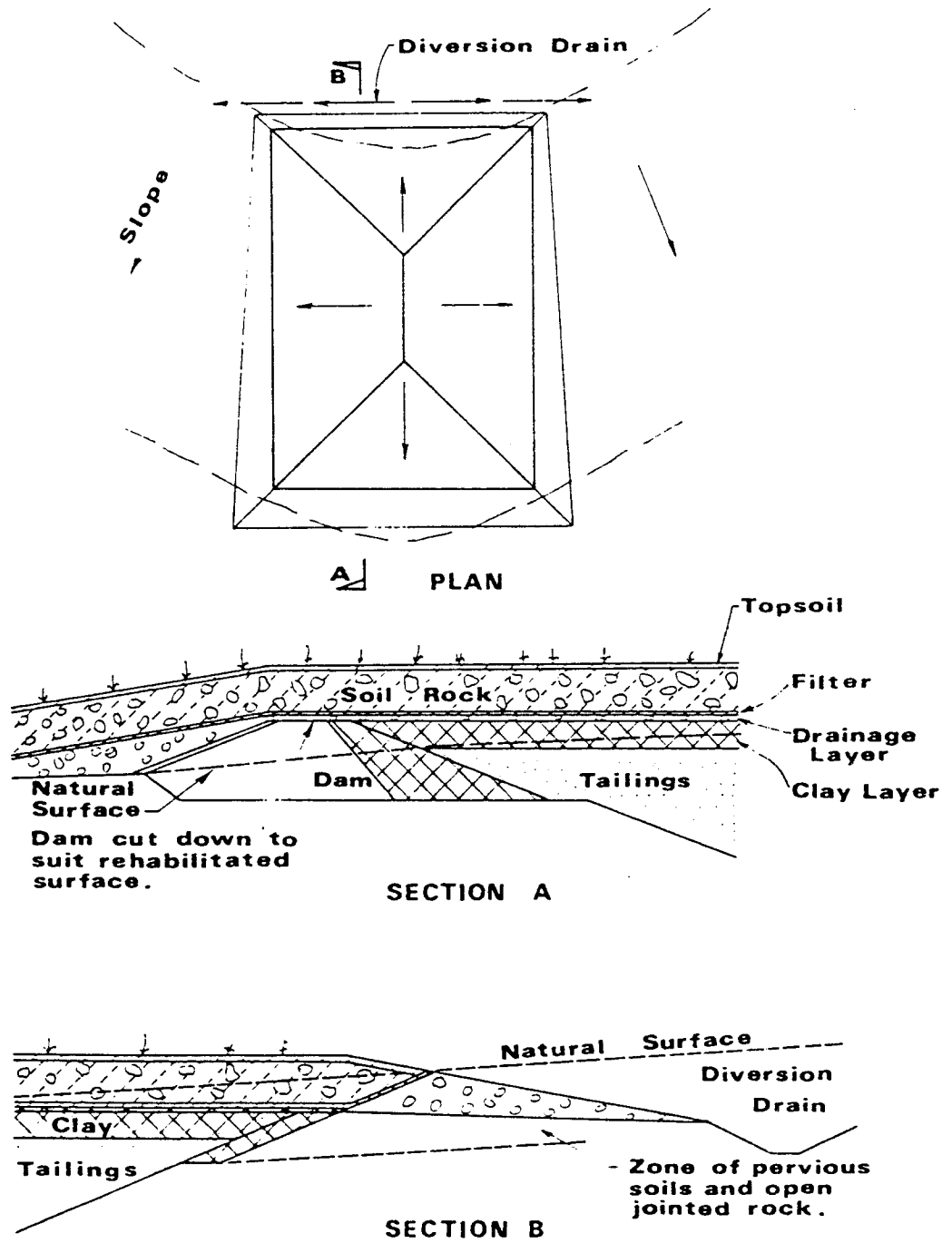


Figure 3. Below Grade Impoundment

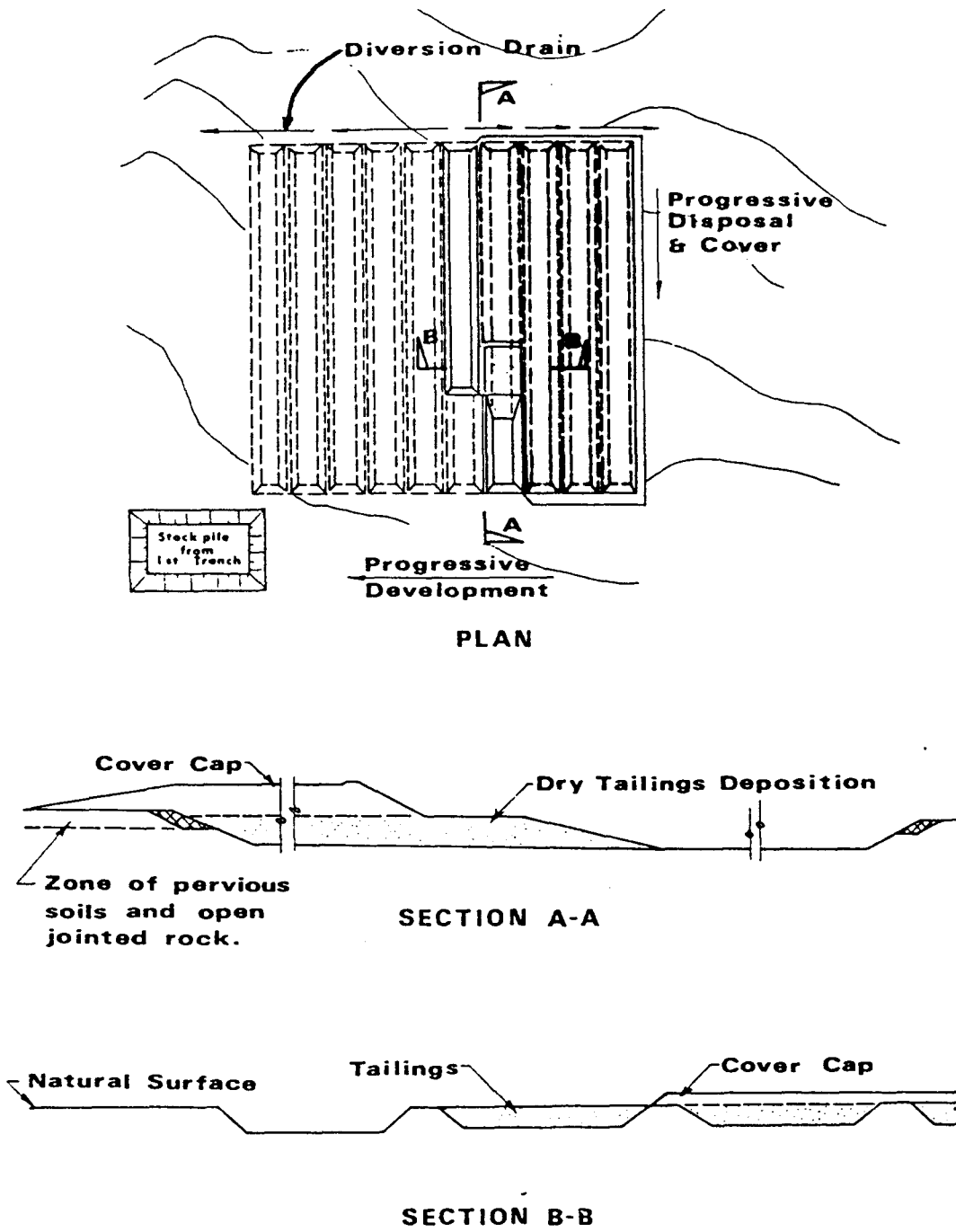


Figure 4. Trench Impoundment (Dry Tailings Management)

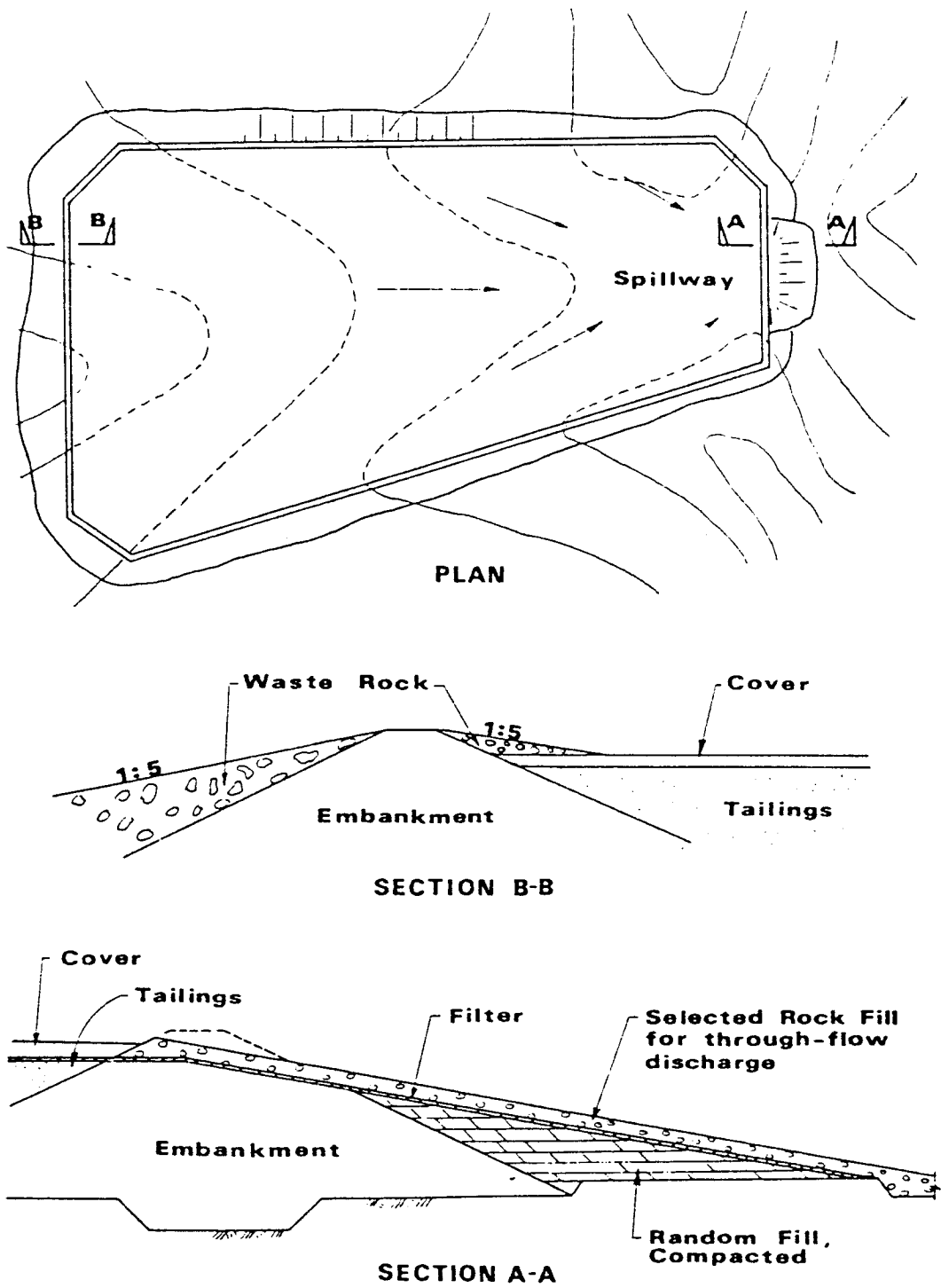


Figure 5. Ring Dyke Impoundment

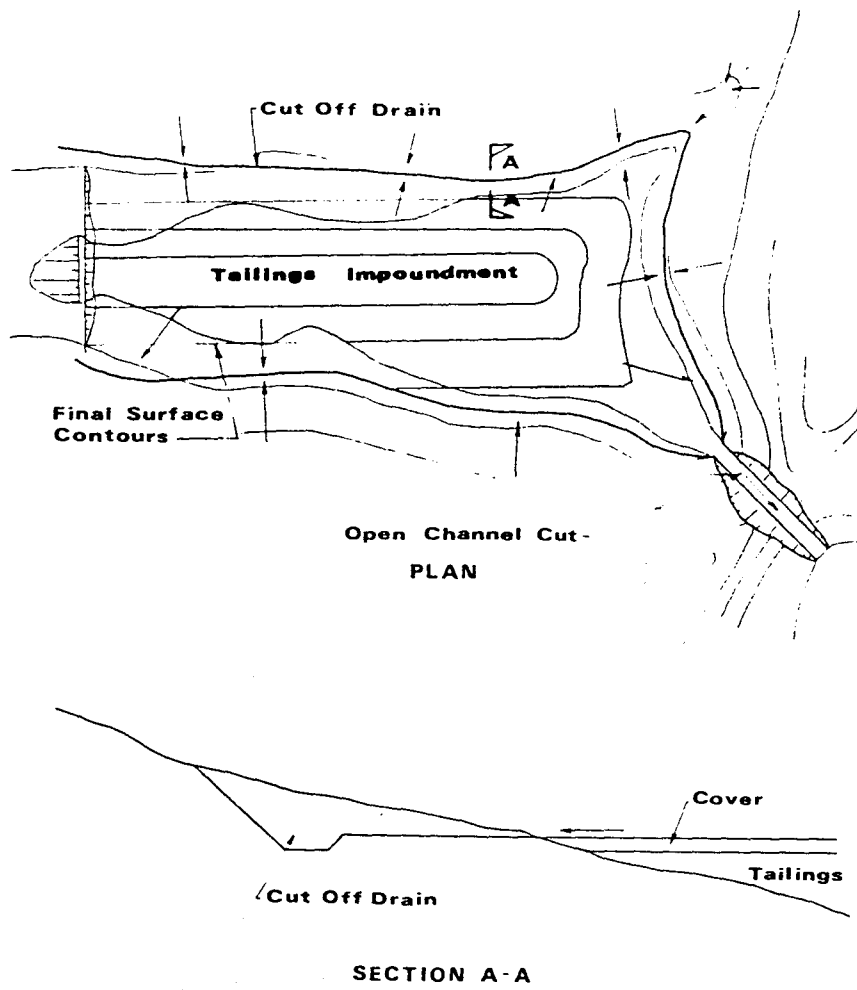


Figure 6. Valley Dam Impoundment

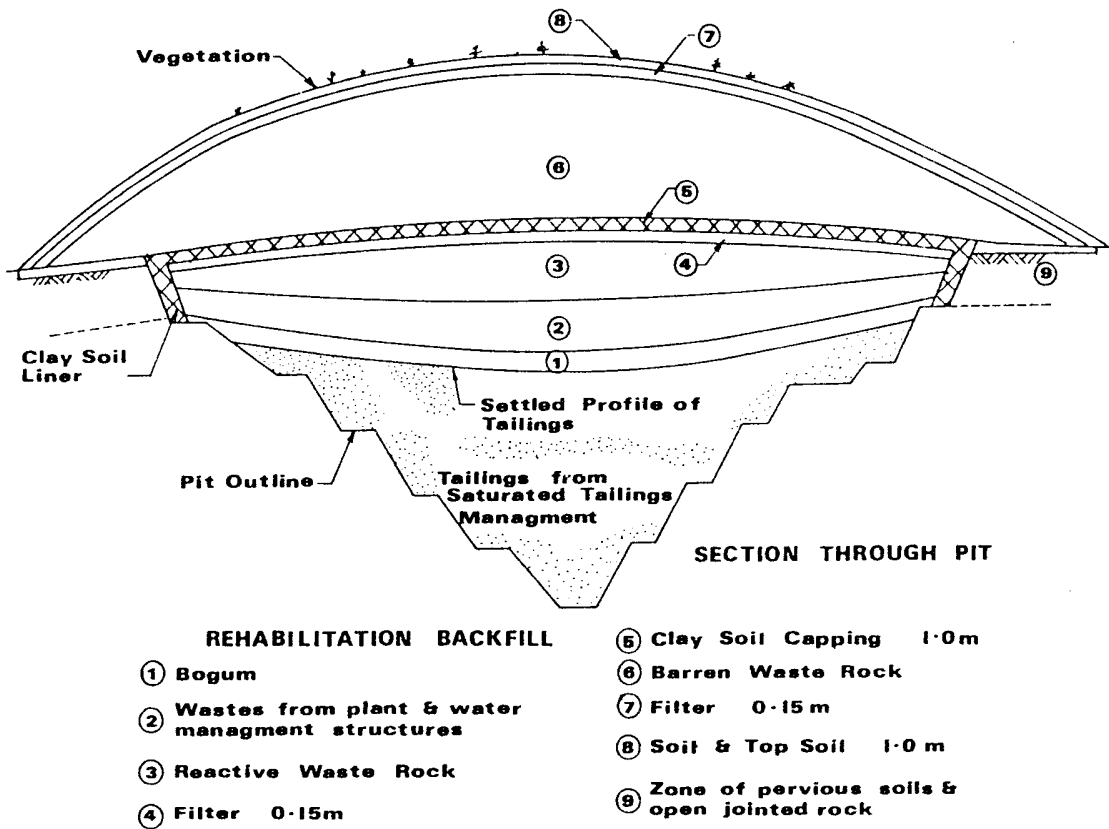


Figure 7. Waste disposal in open pit

#### WASTE ROCK AND ORE STOCKPILE MANAGEMENT

At the Rum Jungle uranium mine the waste rock dumps were major contributors to the environmental degradation caused by the abandoned mine. Rehabilitative measures have already been shown to be successful, although the benefits have yet to be fully determined. The measures adopted included:

- . reshaping the heaps to reduce slopes, provide berms and improve drainage
- . covering with a low permeability zone covered by a growing medium and
- . drainage channels and structures.

The measures were costly and very late in preventing contamination of surface and groundwaters. However, shortly after completion of the works monitoring demonstrated that:

- . the rates of reaction within the piles were reduced;
- . the movements of gases within the piles were reduced;
- . the movements of water through the piles were reduced and
- . the effect was to dramatically reduce the production and leaching of soluble contaminants into the environment.

Measures incorporated into pile management from the outset can serve to reduce all such impacts including the dispersion of radioactive gases and particles.

The volumes of waste rock arising from a mine are site specific. As a general principle there will be considerably more waste rock than tailings (except from underground workings). In order to remove all the economic ore the dimensions of an open cut are determined by the geotechnical requirements to achieve safe pit slopes, the volume of the excavation increasing approximately in proportion to the depth of excavation cubed.

Out of the excavation comes:

- (a) ore, the grade of mineralisation deemed to be economic to mill and concentrate uranium;
- (b) below ore grade uranium mineralisation (bogum), the material below ore grade but above the grade used to determine specified material; and
- (c) wasterock, all excavated material that is not specified material.

Distinction between the grades of rock is best achieved in the mine pit and won separately. This is confirmed by passing trucks under discriminators as they pass from the pit. The rock can be further subdivided on mineralisation, rock type and chemical reactivity. The classification and separation of rock is an important component of efficient management leading to appropriate long-term measures.

Contaminants can be released to the environment from stockpiles generally by wind erosive action, rainwater action (run-off and infiltration which produce erosion and seepage) and exhalation of radon gas.

Wind erosive action is generally limited in its impact to the period during mining until a stable rocky surface is established.

Rainwater falling onto a pile is distributed in four ways namely evaporation and evapo-transpiration, run off, infiltration and surface and subsurface storage. The proportions of these depend on the shaping of the surface, the porosity of the materials, and the intensity of the rainfall.

These provide mechanisms for erosion of piles, leaching of materials from piles and the build up of groundwater under piles producing springs.

Exhalation of radon gas (and the circulation of other gases, importantly oxygen) depends on the ability of the gas to move through the pile. Two mechanisms, advection and diffusion, are dominant and depend on the presence of porous zones and driving gradients.

The exhalation of radon is also dependent on the rate of production within the particles comprising the dump. This is reported to be proportional to the ore grade.

#### Construction Techniques

The categorisation of the rock to be excavated from the mine should generally be delineated, in terms of its mineralogy, radioactivity and chemical reactivity, before excavation of the pit commences.

A waste rock and ore management plan should be developed, around the anticipated materials, which identifies the balance of materials and the peak and ultimate volumes to be stockpiled.

Ore stockpiles and bogum should be made on prepared pads which isolate the specified material from ground and surface waters. Should the stockpile remain undisturbed it should be covered so as to

- (a) reduce the water infiltrating and percolating through the heap
- (b) reduce the movement of gas within the heap, and
- (c) reduce the wind erosion of the surface of the heap.

Unused bogum should be disposed of inside a pile, tailings impoundment or the open cut where it is suitably isolated from the pathways to the environment.

The volume of waste should be minimised and radioactive and reactive materials treated in such a manner as to effectively isolate them from the pathways to the environment. This can be assisted by using non reactive rock as a buffer in conjunction with engineered measures.

Depending on its mineralogy non reactive waste rock may be suitable for many purposes such as construction of roads, embankments, general filling, cover structures for rehabilitation, and minefill.

If the mine is to be used to dispose of wastes it should first receive the materials presenting the greatest hazard and then these should be covered by non-reactive materials.

The waste materials generated by mining will always present a much greater volume than the original, due to the creation of voids. The bulking would mean that even if the pit were filled to the maximum extent there would be approximately 30% to 50% of the material remaining above the surface. This would be greater when borrow materials are incorporated for special purposes.

The pollution potential of waste rock increases if it has a high sulphide mineral content. These materials may be oxidised chemically, catalysed by bacteria (e.g. Thiobacillus Ferrooxidans), which produces sulphuric acid. Sulphuric acid solubilises heavy metals present in the rock and the subsequent waters, known as acid mine drainage, present a chronic hazard. Separation of sulphidic material from an oxidising environment and minimisation of water available for leaching has been an effective means of reducing the impact.

During the operational phase, drainage from waste rock piles that are a potential source of pollution should be collected and directed to the restricted release zone as portion of the water management scheme.

Waste rock dumps should be designed to provide:

- . stabilisation against wind and water erosion
- . stable slopes
- . reduction of airborne dust
- . minimisation of acid drainage from the dump
- . shape and contour of the dump so it will blend aesthetically into the natural environment
- . revegetation to obtain a self-sustaining vegetation on the surfaces of the dump
- . restoration of the dump area to a specific productive use.

Small volumes of sulphidic material could be disposed of

- (a) in the mine pit at a level well below water table and sealed by clay soil to prevent inflow of oxygenated water
- (b) by disposal with the tailings
- (c) by disposal in an above ground dump
- (d) well sealed with a cover and
- (e) by milling and processing the material to obtain a pyrite concentrate for subsequent disposal.

Large volumes of sulphidic waste rock would probably require disposal in a well sealed above ground dump with a cover structure. Cover structures are discussed in the decommissioning and rehabilitation section.

Alternative management options exist if portion of the waste rock is reactive and portion is barren. In this case the reactive waste rock can be incorporated into the centre of the pile and surrounded by barren rock as a buffer to the environment. The reactive rock could still be isolated from circulation of oxygen and water by appropriate measures.

In all cases the movement of air within the stockpile can be minimised by changing previous pile building practices from end dumping down an advancing face from the top of the dump (giving high slopes of about 37° with the horizontal) to raising the dump in well controlled lifts minimising segregation. The early practice ensured that a highly porous zone at the base of the pile existed allowing a vent for advection into the heap. This was

demonstrated by monitoring gas composition and temperature at one of the piles at Rum Jungle before rehabilitation. A placement consisting of (say) 1m controlled lifts in accordance with rockfill dam practice would

- (a) minimise segregation
- (b) allow placement into its final position without need for reshaping, and
- (c) allow for progressive rehabilitation of the stockpile.

The figures 7, 8 and 9 show some potential methods of waste rock disposal. These methods include:

- . diversion of waters around the dump
- . reshaping dump surfaces to final form
- . carrying out surface drainage works
- . covering some or all areas of the dump with a cover seal to reduce inflow of air and rainwater
- . covering some or all areas of the dump with soil materials suitable for promoting vegetation growth and work required to establish such a vegetation.

#### DECOMMISSIONING AND REHABILITATION

Prior to cessation of operations a final decommissioning and rehabilitation plan must be produced. This plan is the logical outcome of the waste management programme and details the measures to be taken, in the light of experience gained during the operational phase, to implement the final objectives of the waste management plan. This plan continues the theme of site specific solutions to meet the objectives and must provide a rehabilitation strategy which acknowledges that a truly passive system may not be achievable in practice but which, after a period of monitoring and maintenance, minimises the need for ongoing institutional controls.

At the completion of a successfully implemented decommissioning and rehabilitation programme the mining company should be released from all further obligation by the appropriate authority. This requires that the decommissioning and rehabilitation programme be developed in conjunction with the appropriate authority.

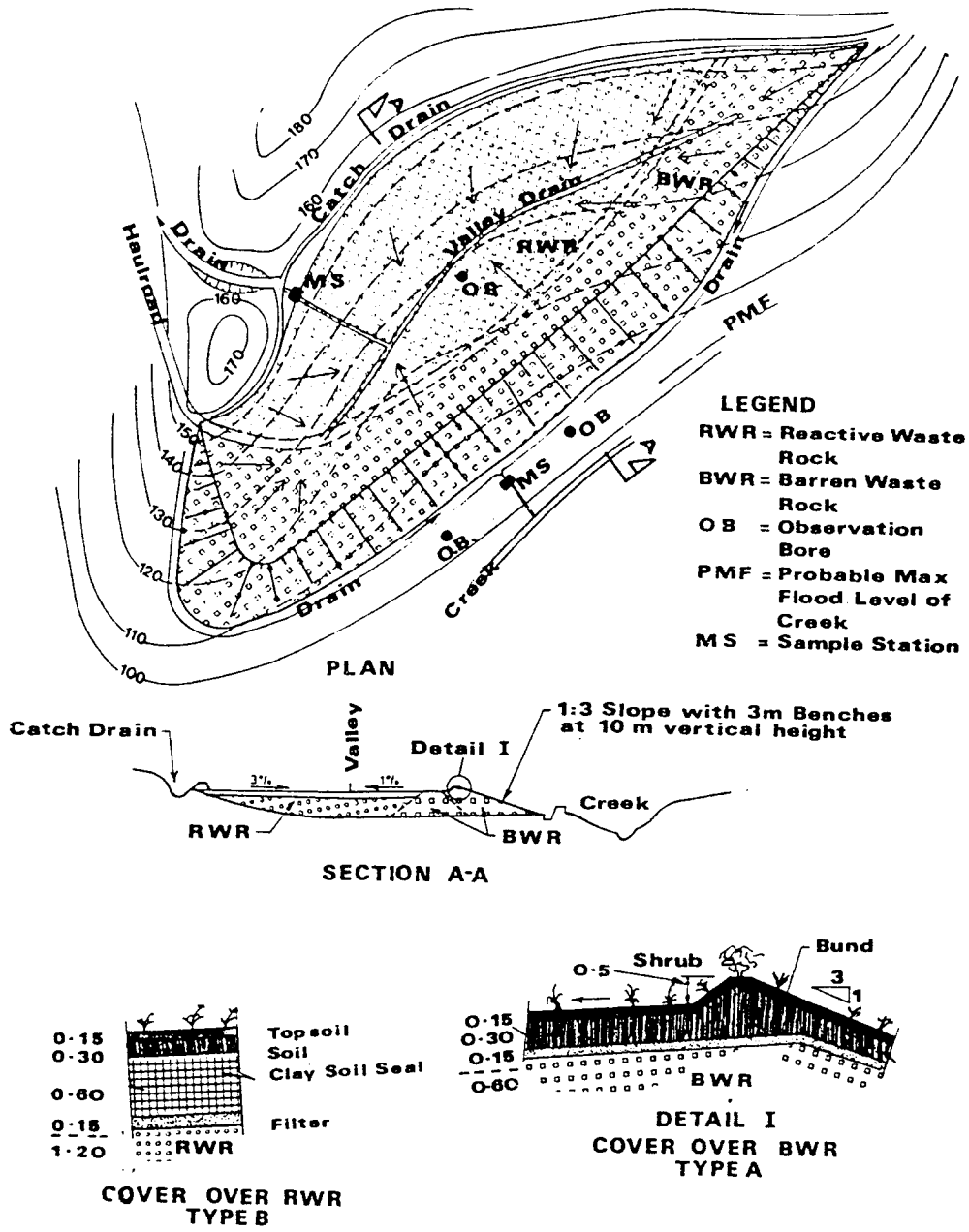


Figure 8. Waste rock dump on side slope.

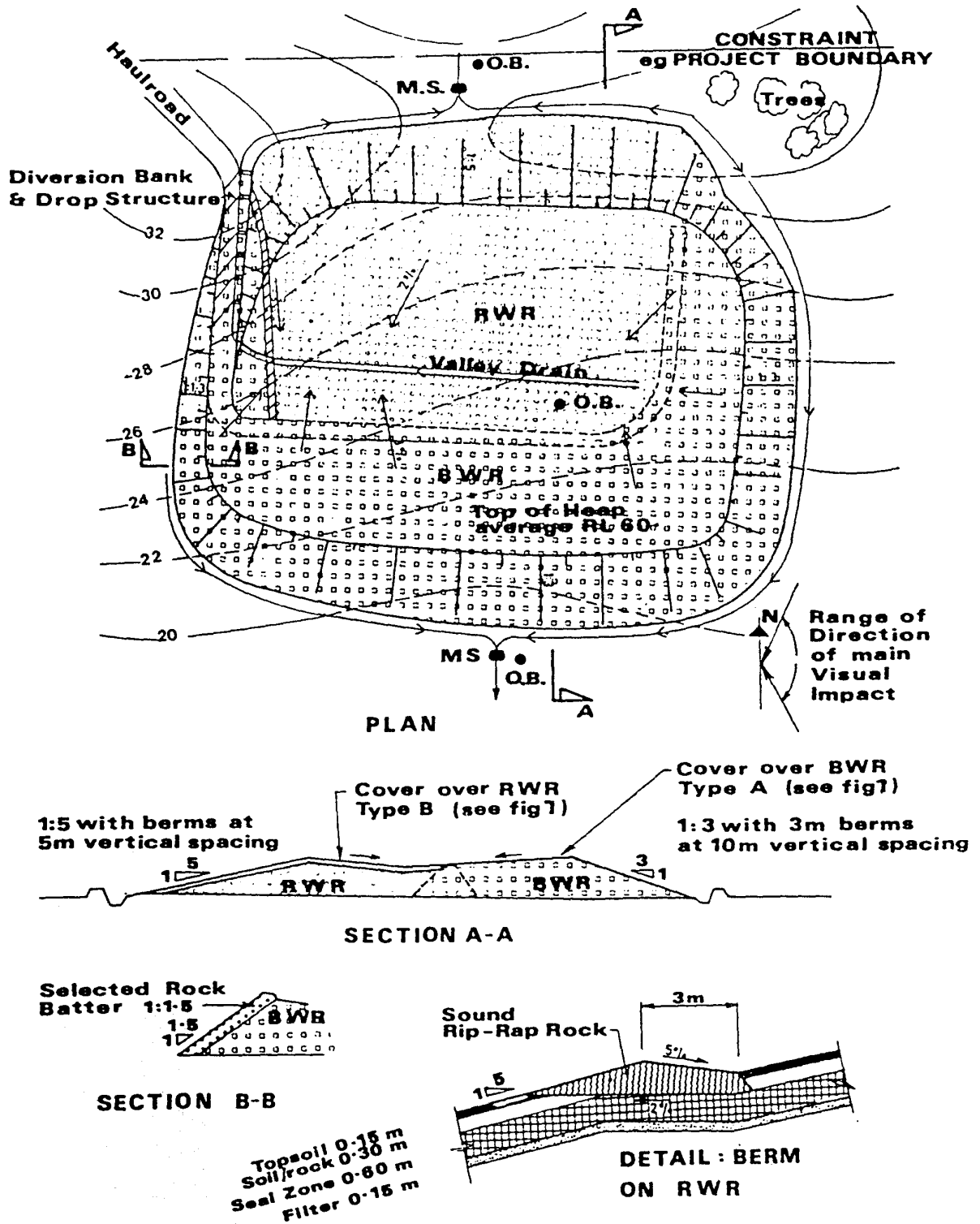


Figure 9. Waste rock heap (For Legend, see Figure 8)

Progressive rehabilitation, where this is possible, is a necessary strategy to ensure that all measures are rehabilitated at the earliest opportunity. This not only allows for some research on alternative measures but ensures that measures are well established, consolidated and proven before divesting responsibility.

Decommissioning of a project site means that all materials, structures and facilities as well as wastes become wastes. Some of these may be decontaminated for transfer to another facility whilst the remainder are to be disposed of on site.

The objective of decommissioning and rehabilitation is:

- (a) to make safe mine workings, mill sites and waste disposal sites
- (b) to eliminate unacceptable health hazards and
- (c) to restore the area, as far as practicable to a condition suitable for its former use, or for other uses.

Decommissioning and rehabilitation programs should aim, in a cost effective way, to

- (a) restrict - gamma radiation;
  - concentrations of radioactive gases and airborne particles; and
  - radionuclide contamination of surface soils in, and emanating from the mine project area, to levels such that public exposure is as low as reasonably achievable, and in any event within prescribed limits.

- (b) restrict, over the long-term, the dispersal of mine products, radionuclides, heavy metals and acids to a rate which will not significantly disrupt ecosystems and which is, in any event, within prescribed limits
- (c) remove from the mine project area risks to health and safety, or limit access to these, in accordance with intended future land use
- (d) render the sites and wastes stable over the long-term
- (e) maintain the diversity of biological species in the area where feasible
- (f) remove structures and restore the land, as far as is practicable, to a condition suitable for its former use or for other uses, and
- (g) re-establish, as far as is practicable (and consistent with the intended use), the visual character of the site.

The end result of any decommissioning and rehabilitation program should be a site compatible with its surroundings, taking into account the future land use of the area, with a minimum requirement for ongoing active maintenance of rehabilitation works.

The rehabilitation measures should take into account environmental effects such as acid drainage, groundwater contamination, soil contamination, erosion and sedimentation, gaseous emissions, airborne particulates, gamma ray emissions, visual impact and long-term stability of the sites.

#### Rehabilitation of Tailings Impoundments, Waste Rock Dumps and Water Management System

The waste management programme implementation ensures that these components are managed in a way which allows for ready rehabilitation. However, there are criteria which must be met for each area. In many cases it is sufficient to collect and concentrate the materials which fall outside these criteria and dispose of them in a way which meets the criteria. In general, criteria for rehabilitation measures are site specific but should take into account radon flux, gamma radiation and water quality. Measures should meet long-term objectives of design life and structural life.

### Progressive Rehabilitation

Where possible tailings should be progressively rehabilitated.

### Cover Caps

Following the site selection and design for operational constraints the single most important aspect of rehabilitation of a disposal site is the "cover cap".

Irrespective of the type of impoundment a cap which will cover tailings, so providing the final encapsulation, is required. Such a cap will have very few inherent advantages and so will require specific design to overcome the disadvantages.

Cover caps, (on tailings and where required elsewhere), as well as minimising emissions of radiation, radon exhalation, and preventing erosion and dispersion perform an important role in reducing the percolation rate of water through the impoundment. A well designed cover cap would become the controlling factor of the seepage hydraulics of the rehabilitated facilities.

The cover cap is to be thick and to contain erosion resistant upper layers. The upper layers in conjunction with a vegetation cover provide a storage for infiltration which is removed by evapo-transpiration. An upper layer/vegetation layer correctly designed could thus prevent infiltration before the underlying impermeable clay layer of the cap came into effect.

### Zoning of Cover Caps

Generally, cover caps are multi-purpose and should be designed in a zoned configuration which utilises conservative thicknesses because of the difficulties of control during construction, the variability of the materials to be used, and the need to maintain function under settlements and natural forces over periods orders of magnitude longer than those envisaged for the design of civil engineering structures.

The zoning of the cover cap will be influenced by the many site specific factors but should contain zones similar to those shown below.

- . The top zone will generally consist of a rocky topsoil only lightly consolidated. The function of this zone is to provide a growing layer and moisture storage which would enable the initial and evolving vegetation to become established and sustained. The rocky nature of the topsoil should provide protection against erosion by

wind. In arid regions this layer may be more appropriately a rock material giving a final rehabilitated surface of a "gibber plain" similar to the surrounding area with no deliberate attempt to establish vegetation. Followed by:

- . A random soil or soil-rock zone compacted to reduce its permeability and increase its resistance to erosion but still able to provide soil moisture storage for evapo-transpiration needs. Followed by:
- . A filter zone of durable rock graded in accordance with conservative design rules. This layer serves to prevent loss of function of the layers above by migration of the finer particles under the influence of seepage. This layer will usually require manufacture and will carry a high unit cost. Followed by:
- . A pore breaking zone of durable rock containing sand to gravel sized particles with little, if any, silt to clay size particles.

This layer:

- breaks the capillary forces between the upper zones and the tailings so preventing the migration of salts towards the surface under negative pore pressures;
- provides a drainage medium and storage for pore water released from the tailings during consolidation; and
- provides a zone of protection from root penetration into the lower tailings and clay.

The zoning shall include;

- . A well compacted clay soil zone of material selected for its low permeability property when compacted. This is the main protective zone of the cover and minimises the infiltration of rainwater from saturated zones above into the tailings. In addition the thickness required, the nature of the material and the need for control of moisture content during compaction (and the retention of this moisture by protected compacted soils) for a 1 m thick clay soil zone will provide effective reduction in radon exhalation and surface gamma radiation.

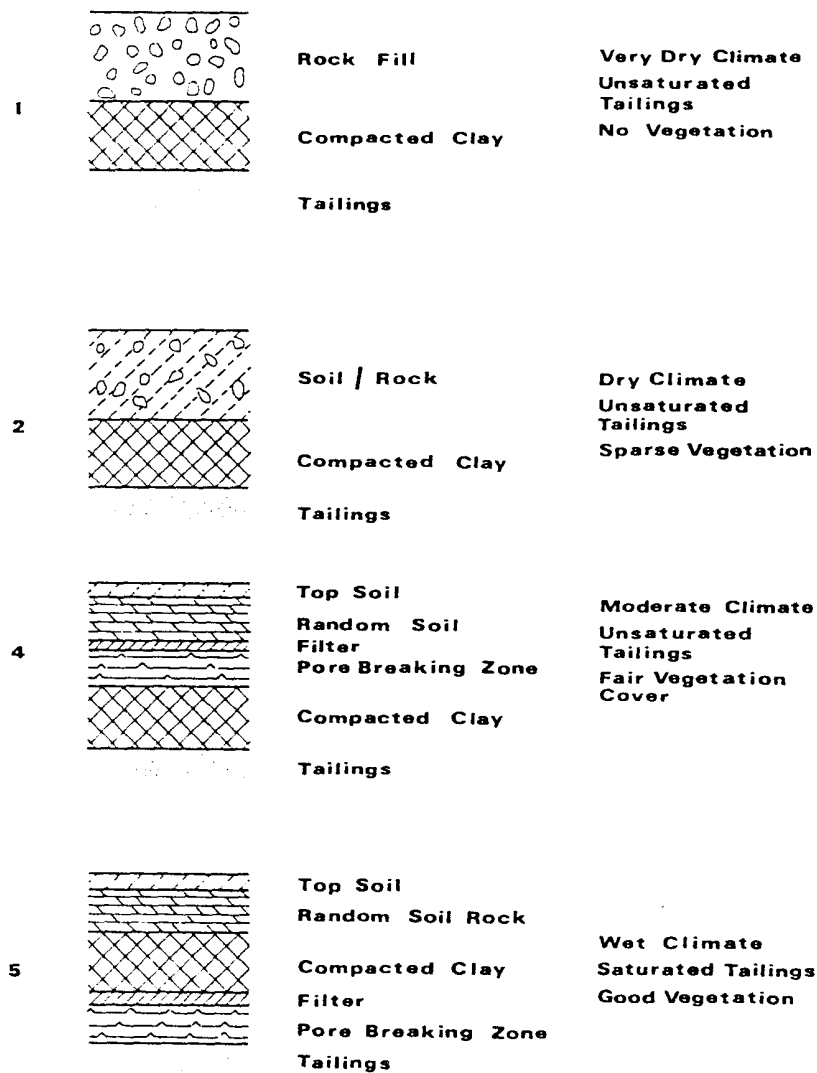


Figure 10. Zoning in cover structures

Figure 10 shows arrangements which could be applied to zoning in different climates.

The drainage pattern and thickness of a cover cap have a marked effect on the amount of water available for percolation through the wastes. Figures 11 to 15 demonstrate the effect drainage pattern and thickness have on radiation, radon flux, seepage and viability of vegetation.

Consequently, thick cover caps and drainage off the cap, in preference to the formation of a pond, are required.

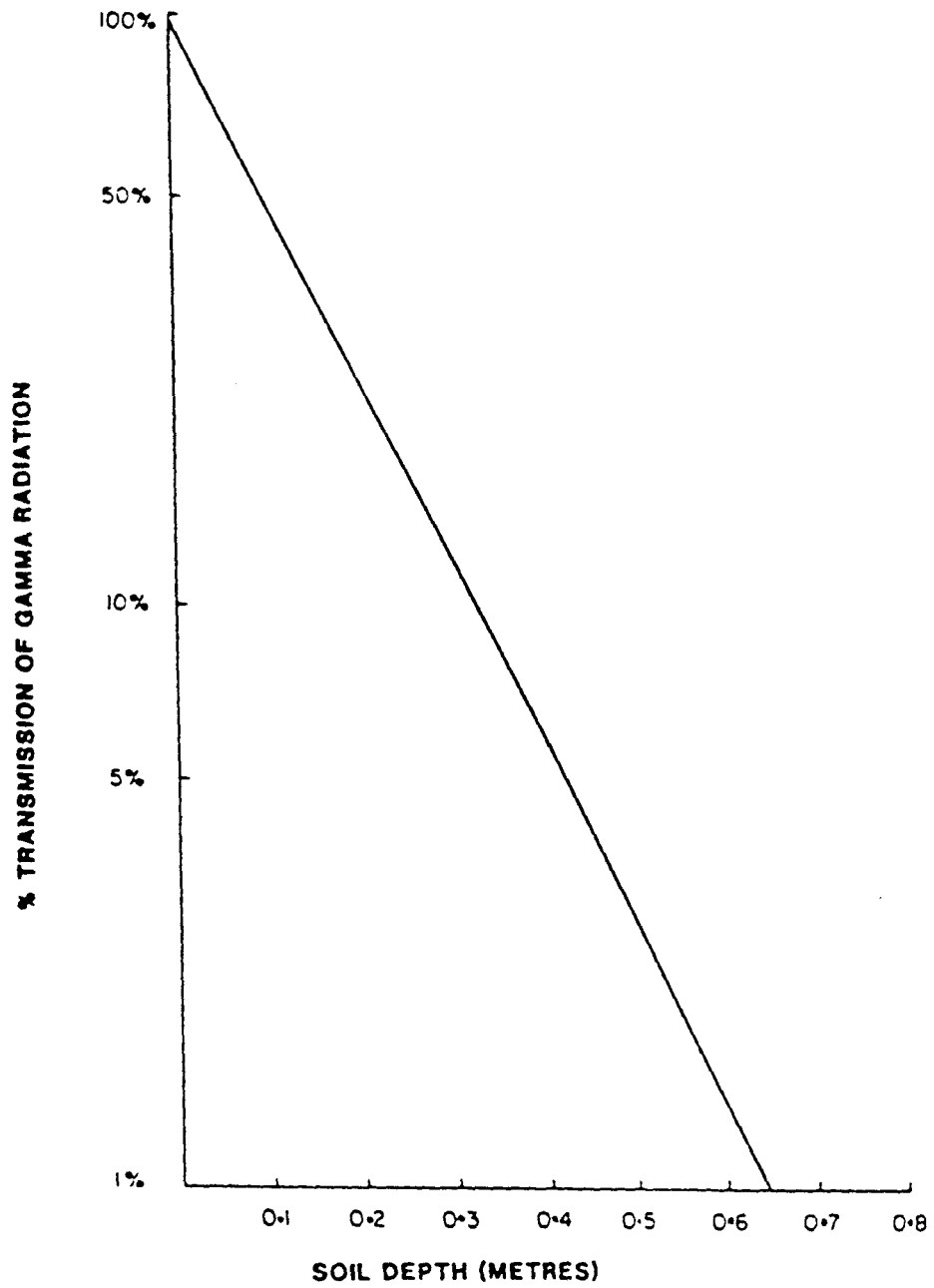


Figure 11. Attenuation of gamma radiation from  $^{238}\text{U}$  series by soil (Build-up Effects are not taken into Account).

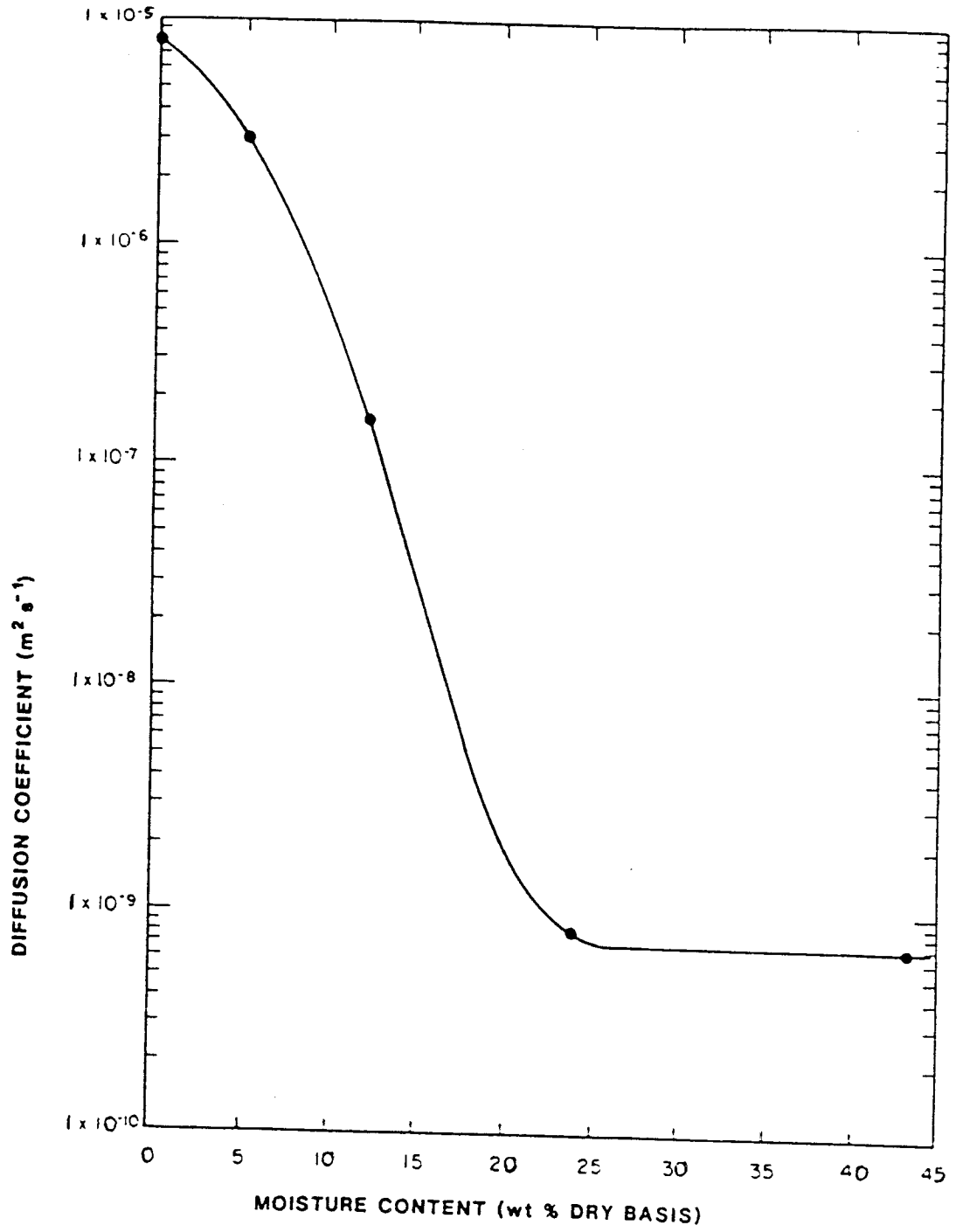


Figure 12. Effect of moisture content on diffusion coefficient.

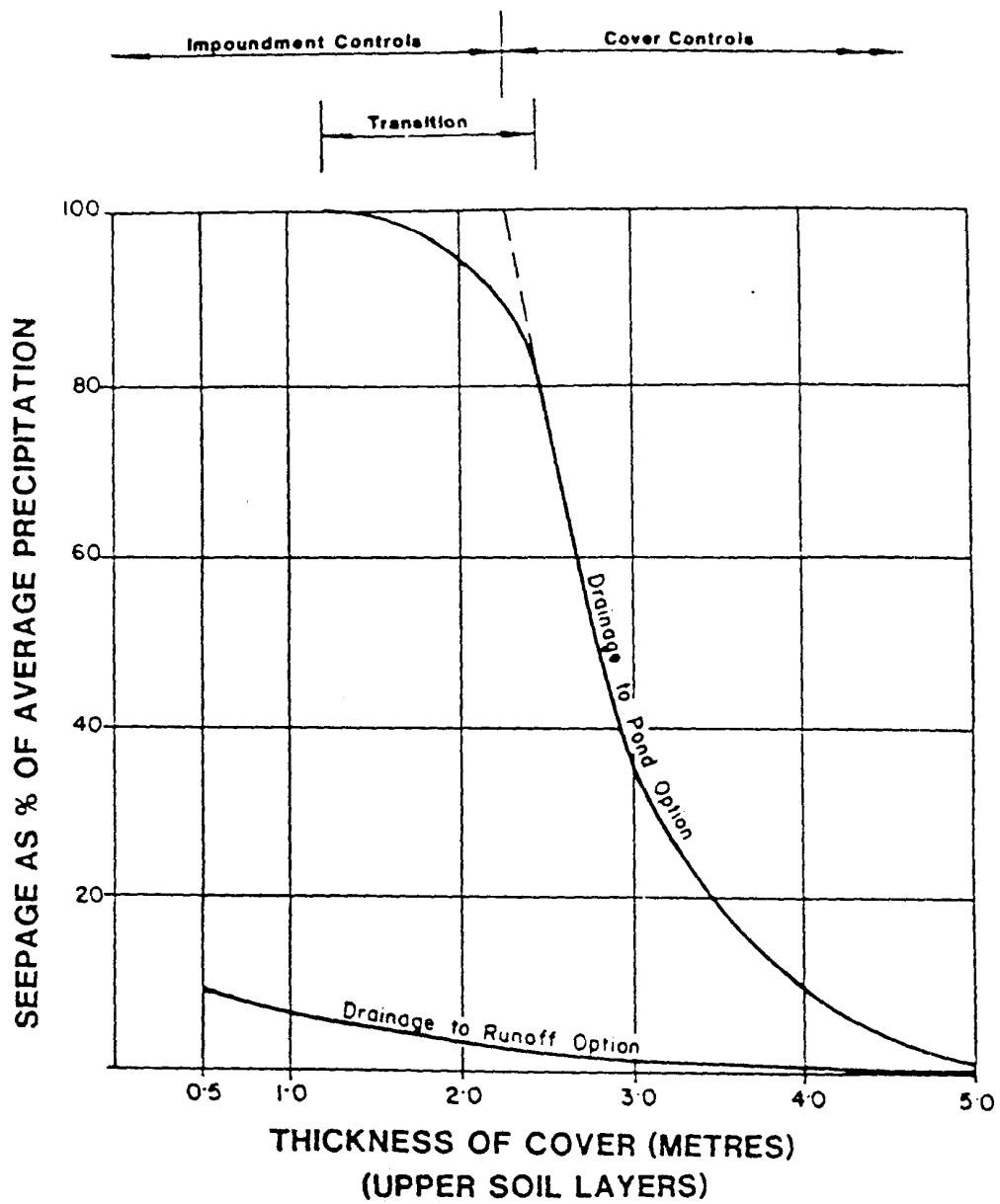


Figure 13. Comparison of cover drainage options with maximum operational seepage.

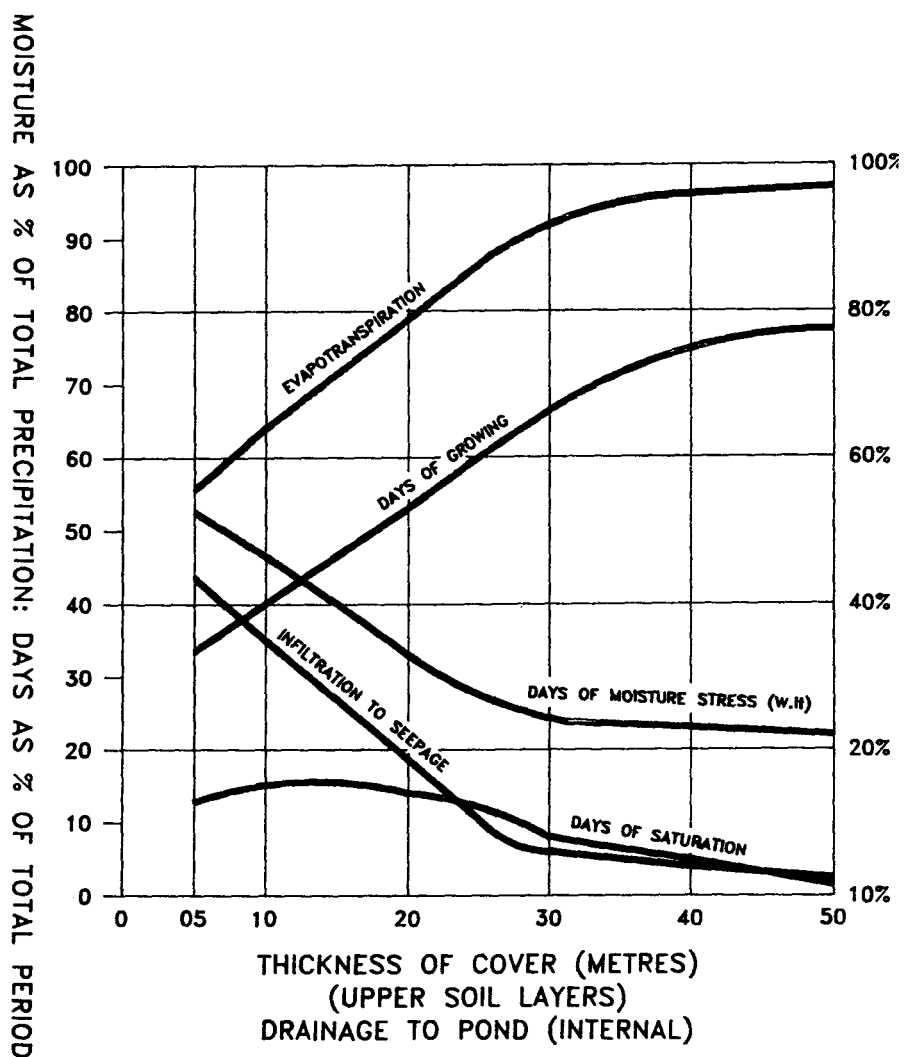


Figure 14a. Study of moisture/thickness relationships for tropical climate, zoned cover (9 Years of Data).

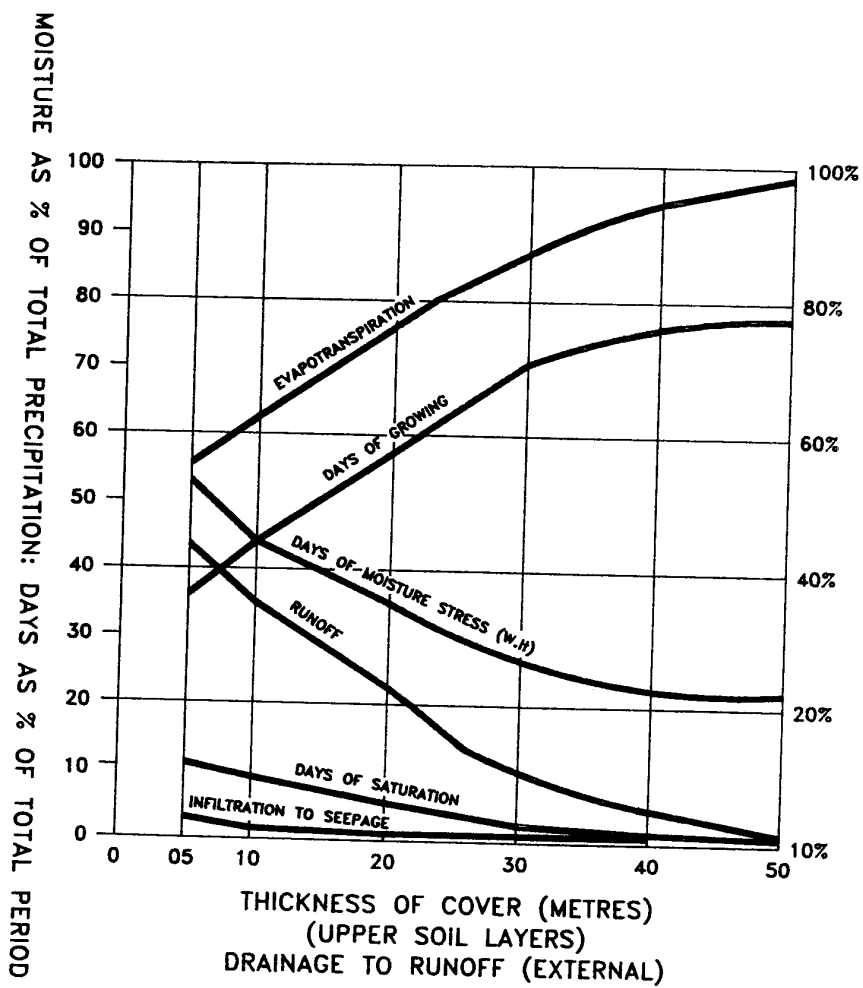


Figure 14b. Study of moisture/thickness relationships for tropical climate, zoned cover (9 Years of Data).

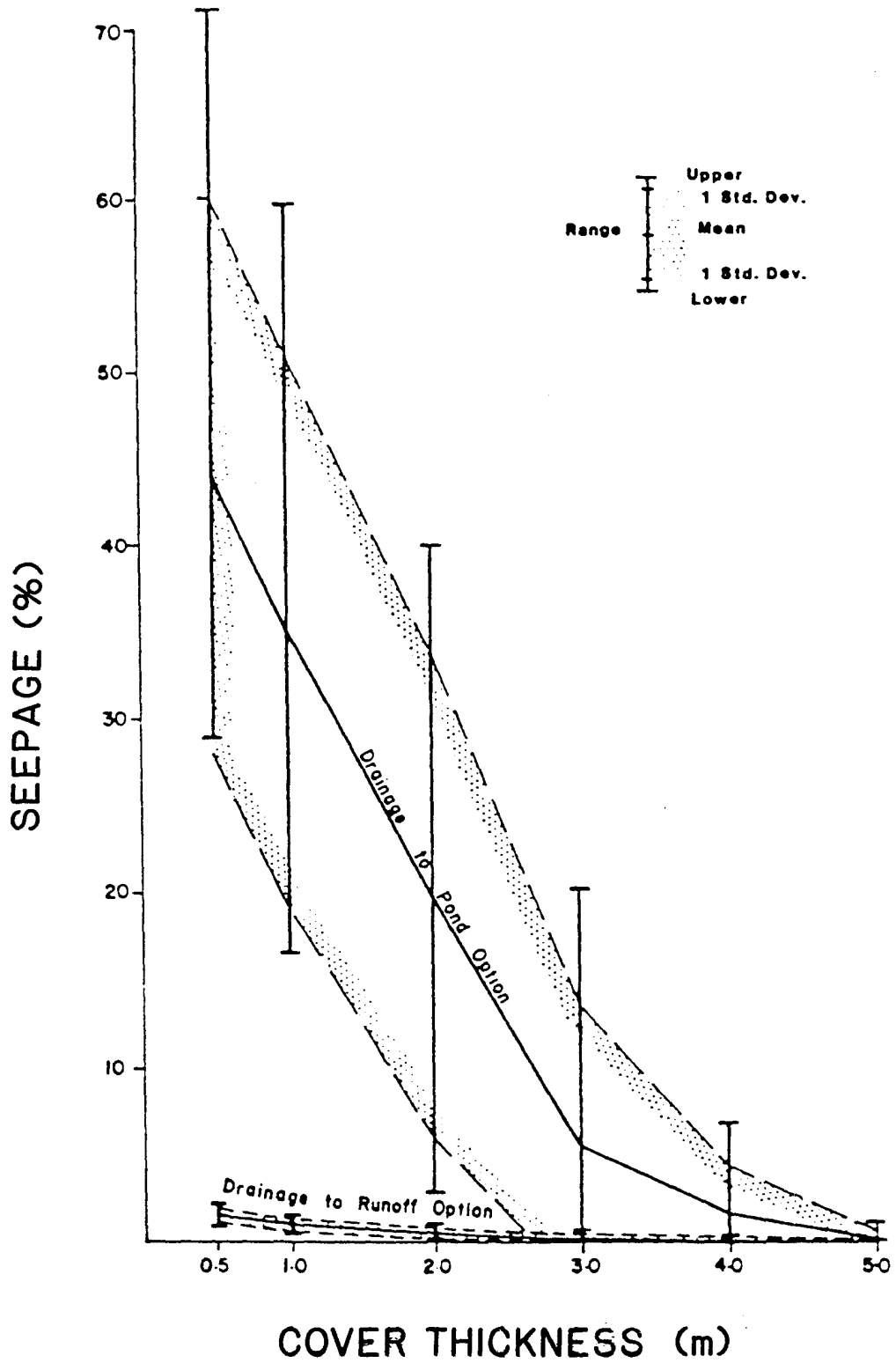


Figure 15. Variability of seepage with cover thickness (upper soil layers) for a simulation over 9 years.

### Long Term Integrity

In order to retain integrity over the long-term caps must be graded and designed to respond to the long-term differential settlements which will occur as excess pore pressures are dissipated from tailings and consolidations occur. At Dysons open cut (Rum Jungle) consolidation of tailings has caused extensive settlement of the cover which will require remedial work. A tailings disposal method which achieves high densities will reduce this need for follow up action.

Figure 7 shows an arrangement for disposal of wastes and rehabilitation which meets most of the principles discussed in this paper.

Design life is the period after completion of an engineered structure, during which the structure and all its components are expected to perform in accordance with their design objectives. Structures for use by man are usually expected by their designs to be continuously occupied or used, with accompanying maintenance and periodic renovation. In this context 100 years would be a conservative target for the design life of major structures.

Structural life is the period over which a structure is expected by the designer to continue to perform its basic functions, even if at a reduced level. Structural life is a measure of the useful life of a structure in terms of its performance and is obviously capable of being extended by renovation and maintenance activity. If this performance was measured as the period over which the release of contaminants to the environment was at a rate below the assimilative capacity of the regional environment, structural life could be expected to extend to thousands of years.

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