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CODE OF PRACTICE ON THE MANAGEMENT OF RADIOACTIVE WASTES FROM THE MINING AND MILLING OF RADIOACTIVE ORES (1982)

GUIDELINE

Decommissioning and Rehabilitation of Uranium Mine, Mill and Waste Disposal Sites

Date of adoption or revision	:	1985
Primary related Clause	:	15
Other related Clauses	:	5(2)(a), 5(7), 7(1), 14

Draft

February, 1985

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INTRODUCTION

1. The decommissioning and rehabilitation of uranium mine, mill and waste disposal sites is an integral part of any uranium mining and milling operation. Decommissioning and rehabilitation measures ensure that sites do not constitute a continuing source of unacceptable environmental pollution and radiation exposure.

2. The Code of Practice on the Management of Radioactive Wastes from the Mining and Milling of Radioactive Ores (1982), referred to in this Guideline as the "Code", sets out three basic requirements in relation to the rehabilitation of sites where radioactive ores have been mined. These requirements are:

- that sites where radioactive wastes arising from exploration, mining, milling and decommissioning operations have been deposited shall be rehabilitated in accordance with the approved waste management program and to the satisfaction of the appropriate authority (Clause 15(1));

- the waste management system shall utilise the **best practicable technology** and shall be such as to ensure that the release of radioactive material will be minimised (Clause 7(1); and

- the final disposition of radioactive wastes and the rehabilitation of the site shall be such that the need for subsequent inspection, monitoring and maintenance is minimised, and preferably rendered unnecessary (Clause 7(1)).

3. The first of these requirements recognises that the successful rehabilitation of a mine project area can best be achieved if, from the initial planning stage onward, all operations are planned and carried out taking into account final rehabilitation requirements. If this is not the case, then rehabilitation will usually involve more effort, be more expensive and probably less successful. The Code therefore requires that the initial waste management program for a particular mining project also canvass proposals for the rehabilitation of the site (Clause 5(2)). These proposals would be refined and updated progressively during the life of the operation, and in the light of operating experience (Clause 5(3)). Before the permanent cessation of operations a final decommissioning and rehabilitation plan should be submitted to the appropriate authority for approval, as required by the Code at Clause 5(7).

4. The second requirement concerns the need to ensure that sites where radioactive materials have been deposited are rehabilitated such that the release of radioactivity from the site is minimised and the exposure of members of the public to radiation is as low as reasonably achievable and below the limits prescribed in the relevant Schedules to the Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (1980) (Clause 7(2)). The sense in which

'minimised' is to be understood is implicit in the definition, in the Code, of Best Practicable Technology ie. Best Practicable Technology is that technology, from time to time relevant to a specific project, which enables radioactive wastes to be managed so that radiological risks to people and the environment are minimised, having regard to a number of specified factors. These factors include the available technology, the cost relative to the protection achieved, the adequacy of protection already being achieved, local site conditions and the potential hazard of the wastes over the long term.

5. The third basic requirement concerns the need to ensure the construction of systems for long term radioactive waste management which do not require active maintenance to preserve their efficacy. Recognising that a truly passive system may not be achievable in practice, the Code requires that dependence on ongoing surveillance and maintenance be minimised. This limits the class of suitable technology for the long term to that which does not depend on active maintenance to ensure that it performs according to specifications throughout its design life.

6. The Code requires a reasonable post-rehabilitation monitoring and maintenance period (Clause 15(3)) . During this period the radiological and non-radiological performance objectives which were established specifically for the site can be assessed. This period will be variable and dependent on operational procedures and site-specific environmental characteristics, and would be expected to be at least five years. If the operator can demonstrate that the site meets performance objectives approved by the appropriate authority, it should then be possible to release the operator from further responsibility for the site.

7. In developing proposals, and the final plan to decommission and rehabilitate a particular site, there is a need for continuing interaction between the owner/operator/manager and the appropriate authority. This is to ensure the most appropriate decommissioning and rehabilitation plan is adopted for the site, and that the plan takes into account future land use requirements for the area. While flexibility in developing rehabilitation proposals is important, the strategy for final decommissioning and rehabilitation needs to be agreed well before the permanent cessation of operations.

8. The Code requires that rehabilitation measures should be undertaken progressively during mining/milling operations whenever practicable (Clause 15(1)). As well as being a matter of good site management a progressive approach to rehabilitation provides opportunities to gain practical experience in carrying out successfully the measures required after mining/milling activities cease.

9. The Code provides for the management of radioactive wastes from mining and milling operations which are temporarily suspended (Clause 4(1)(c)). The term "temporarily suspended"

is not defined in the Code but is interpreted here to mean a decision to suspend operations with the clearly demonstrable intention to resume operations at some future date. Before a temporary suspension of operations a modified waste management program is required to be submitted to the appropriate authority for approval (Clause 5(4)). This program should include appropriate proposals, to cover aspects of maintenance, decommissioning and rehabilitation.

10. Also of concern are the non-radioactive contaminants in the wastes, in particular heavy metals, which can be damaging to the environment and a hazard to man. While the Code is directed towards the management of radioactive wastes, Clause 4(3) requires that in implementing its provisions due regard be given to the requirements of the appropriate authority pertaining to non-radioactive contaminants in the wastes. However it is apparent that effective rehabilitation strategies must take account of the chemical characteristics of the wastes - including both the radioactive and the non-radioactive contaminants. Accordingly, in this Guideline references to waste should be taken, where appropriate, to include non-radioactive components.

Scope of the Guideline

11. This Guideline is intended to provide an overview of the objectives and strategies for the rehabilitation of uranium mine, mill and waste disposal sites. As each site will have specific rehabilitation requirements, the options discussed are necessarily of a general nature, although specific options are canvassed where possible.

12. For the same reason it is not possible to identify quantitative standards for application to any rehabilitated site (to cover such parameters as soil erosion rates, water quality, gamma ray emissions and radon emissions). However, the Guideline provides a methodology by which such parameters can be addressed, before appropriate standards for a specific site are determined, in consultation with the appropriate authority.

13. This Guideline does not canvass all the rehabilitation requirements relevant to sites where the mining of uranium is undertaken by in situ leaching or where uranium is recovered from heap leaching operations. The specific requirements are outlined in the Guidelines: The Mining of Uranium by In Situ Leaching and Management of Heap Leach Piles. Similarly, specific rehabilitation requirements in relation to tailings impoundments, waste rock heaps, ore stockpile areas and water management structures are discussed in the Guidelines : Tailings Impoundment for Uranium Mines; Waste Rock and Ore Stockpile Management; and Design and Operation of a Water Management System for a Uranium Mining and Milling Operation.

OBJECTIVE OF DECOMMISSIONING AND REHABILITATION

14. Following the permanent cessation of a mining/milling operation, the objective is to make safe mine workings, mill sites and waste disposal sites; to eliminate health hazards; and 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:

- remove risks to health and safety;
- restrict over the long term the dispersal of mine products, radionuclides, heavy metals and acids to a rate which will not result in unacceptable environmental damage;
- render the sites and wastes stable over the long term;
- where feasible, maintain the diversity of biological species in the area;
- restore the land, as far as is practicable, to a condition suitable for its former use or for other uses; and
- re-establish, as far as is practicable, 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.

Major Problem Areas to be Addressed in the Decommissioning and Rehabilitation of Mine Project Areas

15. Mining, milling and waste disposal may result in major environmental problems unless appropriate rehabilitation measures are implemented. These problems include acid drainage, groundwater contamination, erosion and sedimentation, gaseous emissions, airborne particulates, gamma ray emissions, visual impact, and the long term stability of the sites.

16. **Acid drainage** (from active or abandoned sites) is perhaps the major environmental concern. Low pH waters may dissolve minerals containing radioactive elements and heavy metals. Acidity combined with deposited salts and heavy metals can prevent plant growth. In addition, downstream watercourses may become contaminated and be incapable of supporting life.

17. **Groundwater contamination** - The processes which create acid drainage have the potential to contaminate groundwater. Near surface groundwater may become a source of pollution when it returns in water courses or as springs. Deeper groundwater resources may be rendered unsuitable as pollution fronts expand. The transport of pollutants by groundwater may be a slow process and serve as a long-term source of pollutant well after the mine has been decommissioned and rehabilitated. Strategies should be aimed at minimising the contribution of polluted water to the groundwater by minimising the driving mechanisms and separating contaminated waters from the groundwater. Interaction between "impermeable" liners and the polluted waters may provide this separation.

18. **Erosion and sedimentation** - Changes in slope and vegetation due to rehabilitation work may result in an increase in erosion and sedimentation by rainfall and wind. Downstream riverine environments could become unattractive for habitation by biota if attention is not given to aspects of soil erosion and subsequent sedimentation. Erosion can lead to increases in the level of radiological and non-radiological contaminants unless non-mineralised materials are used.

19. **Gaseous emissions** can create significant air pollution problems. Rehabilitation works should aim at minimising the release of radon and any other potentially hazardous gases from waste disposal sites.

20. **Long-term stability of the sites** - As structures age they may deteriorate or collapse leading to the uncontrolled release of contaminants. Conservative engineering design and construction, taking into account geomorphological and geochemical influences in selecting the most suitable available materials, can prolong long term structural integrity.

21. **Airborne particulates** from wind erosion of tailings impoundments, ore stockpile areas and waste rock dumps can sometimes be of concern. The principal dust problem occurs with tailings impoundments on which the surfaces have dried out and have not been adequately protected against wind erosion. Correct management and rehabilitation will protect against wind erosion.

22. **Gamma ray emissions** from radionuclide decay may contribute significantly to the radiation level at the surface of tailings impoundments and other waste disposal sites. Rehabilitation can minimise this problem by ensuring wastes are not deposited in dispersed locations and by providing adequate capping to absorb gamma ray emissions and reduce transport of radionuclides.

23. **Visual impact** of abandoned facilities, rubbish, excavations and waste heaps. Past practice has left a legacy of open cuts, abandoned facilities and poor waste containment. Well executed rehabilitation can make an abandoned site attractive or indistinguishable from the surrounding terrain.

AREAS REQUIRING DECOMMISSIONING AND REHABILITATION

24. The area affected by a uranium mining and milling operation can be defined in a number of ways depending on what particular parameter is being considered. For the purposes of this Guideline it is defined as the area over which the owner/operator/manager has responsibility via some form of legal title. For convenience this area will be referred to throughout this Guideline as the **mine project area.** Within the mine project area particular attention needs to be paid to the area of the restricted release zone (RRZ), which is defined in the Code as "an approved zone about and below a mine and/or mill from which release of radioactive material shall be minimised in accordance with the requirements of the appropriate authority".

25. The mine project area can be sub-divided into the following areas:

- mine and mill sites, including
  - below ground areas;
  - above ground areas;
  - storage and pond areas e.g. waste rock, ore stockpile areas and evaporation ponds;
  - milling and extraction facilities e.g. buildings, plant and equipment;
  - tailings transport and disposal systems e.g. tailings impoundment and pipelines;
  - water management systems;
  - workshops and ancillary areas;
  - mine haul roads;
- other areas, including:
  - residential housing;
  - administrative housing;
  - water treatment plants;
  - sewage works;
  - recreation areas;
  - service areas and roads;
  - bore fields;
  - storage dams; and
  - industrial/residential waste disposal sites.

26. This Guideline is mainly concerned with mine and mill sites. Other areas within the project area, including those items listed in point two of paragraph 25 are not dealt with in detail but rehabilitation of these areas should follow the general principles discussed in this Guideline. Decisions on areas to be rehabilitated and items to be retained would be subject to agreement with the appropriate authority.

CRITERIA FOR REHABILITATION

27. Sites where radioactive wastes have been deposited should be rehabilitated in such a way that any exposure to radiation of members of the public is as low as reasonably achievable and in all cases within the limits prescribed in the relevant schedules to the Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (1980) (Clause 7(2)).

28. In determining the acceptable radiation levels for a rehabilitated site, the appropriate authority may take into account the pre-operational natural background radiation levels which existed at the site. For some deposits the pre-operational background radiation levels at a mine project site may be higher than "normal" environments which are of the order of 0.5 to 1.0 mGy per year (including about 0.3 mGy per year from cosmic radiation) for most places on the earth. Accordingly the appropriate authority may determine it acceptable for a particular site to be rehabilitated to standards such that the radiation levels measured at the rehabilitated site exceed those for "normal" environments. In these circumstances it should be acceptable for the site to be rehabilitated to reduce radiation to levels as low as reasonably achievable taking into account site-specific factors and pre-operational background levels.

29. Pre-operational background levels will vary greatly from place to place in the project area; for example they may be higher over the ore body when compared to other sites within the project area. Similar variations will apply after rehabilitation with higher levels expected over the mine pit, tailings impoundment and waste rock heaps. Consequently it is not feasible to determine a single pre-operational radiation level for the project area which can be compared to a single post-operational radiation level. Verification by field measurement may have little meaning and calculated rates under assumed conservative conditions are preferable. Some field measurements may be required to verify the method of calculation used and for reasons of more academic interest.

Radon Exhalation

30. Radium-226 present in the tailings and in the waste rock material decays to the radioactive gas radon-222. Because radon-222 gas is chemically inert some will escape from the tailings and waste rock particles in which it is produced and diffuse to the pile surface. Airborne radon produces a series of short half-life alpha-emitting products which become attached to minute dust particles and are hazardous when inhaled. Radon exhalation rates from relatively dry tailings piles can be many orders of magnitude (up to 3 to 4) above the natural background radon exhalation rate which is of the order of about 0.037 $Bq/m^2/sec$ (1 $pCi/m^2/sec$).

31. It will be necessary to rehabilitate sites containing mill tailings and waste rock such that the radon-222 exhalation from

the surface of the rehabilitated waste sites does not result in unacceptable radon daughter exposures to local and regional populations.

32. Radon emissions can be controlled by covering the exposed tailings and waste rock with earthen material. The level of attenuation of radon exhalation is related to the type of cover material used, the moisture content of the cover material and tailings, and the design and thickness of the cover layer. Best practicable technology should be used to achieve radon exhalation rates which are acceptable to the appropriate authority.

33. Any radon exhalation rate proposed as the design objective for the rehabilitated radioactive waste disposal sites should be tested by field measurement of radon flux in air over trial rehabilitation sites in order to demonstrate that the proposed design radon exhalation rates could be achieved in practice. Following rehabilitation, the radon exhalation rate over the waste disposal site should be verified by field measurements in order to demonstrate that the design rate has been achieved.

34. Site-specific factors will influence the radon exhalation rate acceptable to the appropriate authority for a particular project. These factors would probably include:

- location of disposal sites relative to actual and potential local and regional populations and the expected effective collective dose commitment from rehabilitated disposal sites;

- expected dose to the most highly exposed individuals or critical group as a result of the proposed radon flux rate for the rehabilitated disposal sites;

- pre-operational radon exhalation rates in the project area;

- possible future land use for rehabilitated disposal sites; and

- cost-benefit analysis for various levels of radon exhalation attenuation.

35. See Appendix I "Mechanism of Radon Exhalation and Methodology for Estimating Radon Exhalation Rates" for guidance on methodology for estimating expected radon flux from rehabilitated waste disposal sites where varying combinations of earthen cover material are to be utilised. The Appendix also discusses procedures for field and laboratory measurement of radon exhalation rates.

36. Various radon flux levels have been proposed for rehabilitated uranium mining and milling waste disposal sites in other countries. In the USA, the Environmental Protection Agency (EPA) has set, as of 30 September 1983, an average radon flux limit for all rehabilitated tailings disposal sites of

0.74 Bq $m^{-2}s^{-1}$ (20 pCi $m^{-2}s^{-1}$). This limit was derived with the use of a cost-benefit analysis (not as described in ICRP 26 and 37) carried out on all expected arisings of uranium tailings in the USA up to the year 2000. The radon flux average is to be applied over the entire disposal area for a period of at least one year. The radon flux limit is thus regarded as a performance standard as well as a design objective. Radon flux measurements are required over the rehabilitated disposal sites to show that the design objective has been achieved. By specifying an average figure over both time and area the EPA has taken into consideration factors which affect the radon flux such as seasonal moisture content, soil discontinuities and variations in the composition of locally available cover material. The Atomic Energy Control Board of Canada has proposed a maximum allowable radon exhalation rate from rehabilitated waste sites of 0.074-0.37 Bq $m^{-2}s^{-1}$ (2-10 pCi $m^{-2}s^{-1}$). However, this proposal is under review and the figures quoted may not be applicable to all sites in Australia.

Gamma Radiation

37. The use of earthen cover material to reduce the radon emanation rate from rehabilitated tailings and waste rock piles will also provide protection from external gamma radiation associated with uranium-238 series daughter products. The thickness of the cover material required for radon reduction should be sufficient to attenuate the gamma radiation to around natural background levels in natural soils.

38. The thickness of earthen cover material necessary to attenuate gamma radiation to one half of its initial value is called a half-value layer (HVL). The HVL for gamma radiation depends on various factors including soil composition, moisture content and degree of compaction. The average HVL of compacted soil is about 0.1 m. A soil cover of 0.5 m will reduce the gamma radiation to about 3% of its initial value from uncovered tailings or waste rock and 1.0 m of soil would reduce it to about 0.1% of its initial value (EPA, 1983). Figure 1 illustrates the percentage attenuation for gamma radiation for a typical soil with increasing depth of soil cover. A tailings pile for a mine treating ore with a grade of about 0.15% uranium would typically have a radium content of about 18.5 Bq/g (500 pCi/g). This would produce a gamma absorbed dose in air of about 70 mGy/year (7 rad/year) at 1m above the uncovered tailings, assuming a homogenous distribution of the radium in the tailings. An earthen covering of 1m would reduce this absorbed dose rate to around 0.07 mGy/year (7 mrad/year). The natural background absorbed dose rate due to uranium-238, thorium - 232 and potassium 40 in natural soils is on average 0.4 mGy/year (40 mrad/year) and ranges from 0.1-0.8 mGy/year (10-80 mrad/year) (Unscear 1977).

Water Quality Criteria

39. Water quality standards for releases (such as seepage or runoff) from a rehabilitated site are site specific and their

determination requires an assessment of the impact of the released wastes (and contained contaminants) on the ecosystem of the receiving waters. This is discussed in the Guideline: Determination of Limits for Radioactive Discharges and Releases.

Design Life, Structural Life

40. The rehabilitation measures employed shall be suitable for the long term management criteria required by the Code. The design life shall be of the order of 200 years. The structural life, assuming a minimum of renovation, should be about 1000 years, which could be extended to some thousands of years by regular attention when required. The concepts of design life and structural life are discussed in paragraphs 113-115 of this Guideline.

FINANCIAL ARRANGEMENTS

41. Financial arrangements should be established at the commencement of a uranium mining and milling operation for the owner/operator/manager to provide for the funding of rehabilitation and long-term site surveillance.

Funding of Rehabilitation

42. Funds are required to cover the cost of rehabilitation works and the subsequent period of monitoring and maintenance. The appropriate authority will determine the amount of funds necessary based on the estimated cost of carrying out the approved rehabilitation program. This amount should be provided by the owner/operator/manager under surety arrangements at the start of the project.

43. Annual reviews should adjust the amount of the outstanding liability in recognition of rehabilitation work performed, inflation, changes in the scope of the operation, changes in engineering plans and any other conditions affecting the cost of work which remains to be done.

44. The effectiveness of rehabilitation works will be evaluated against design criteria during the subsequent period of monitoring and maintenance. It could be expected that the owner/operator/manager would be required to undertake this monitoring and maintenance for a period of at least five years.

Funding of Long-Term Site Surveillance

45. The preferred goal for long term radioactive waste management is that on-going inspection, monitoring and maintenance is unnecessary. The Code recognises (Clause 16) that this may not be possible at least in the short term. Any activities of this nature required after termination of responsibility for the site by the owner, operator or manager will be undertaken by the appropriate authority.

46. The estimated cost of long term site surveillance would be determined to the satisfaction of the appropriate authority on a site specific basis, with offsetting funds paid by the owner/ operator/manager to the appropriate authority prior to the termination of his responsibility for the site. Such payments would be based on public authority estimates of costs of inspections required to check aspects such as erosion rates and to identify and carry out those minor restorative actions which are effective in promoting the long term stability of structures. The funds for long term site surveillance would therefore cover annual professional assessment and minor manual labour.

TEMPORARY SUSPENSION OF OPERATIONS

47. As noted in Paragraph 9, the Code applies to mining and milling operations which are temporarily suspended at any time (Clause 4(1)(c)). Before the temporary suspension of operations a modified waste management program is required to be submitted to the appropriate authority for approval (Clause 5(4)). This program should detail procedures for managing the wastes for the period that operations are suspended and should be developed in consultation with the appropriate authority.

48. When an operation is temporarily suspended it will be placed on a "care and maintenance" basis until the decision is made to resume operations. Before an operation is placed on a care and maintenance basis certain decommissioning and rehabilitation activities will need to be undertaken such that the owner/operator/manager is able to demonstrate that the containment of mine and mill wastes will be adequate during this period. In addition sufficient "care and maintenance" staff having the appropriate technical competence should be on site at all times to ensure:

- the continuous integrity of the waste management system is maintained;
- the monitoring program approved by the appropriate authority is carried out;
- that any maintenance which becomes necessary is carried out; and
- that unauthorised entry to the project area is prevented.

RADIOACTIVE DECONTAMINATION

49. The objective of decontamination is to ensure that doses to individuals after decommissioning are as low as reasonably achievable and below limits given in Schedule 2 and 8 of the Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (1980).

50. As a guide to the application of best practicable technology it is suggested that strenuous efforts are justified to reduce individual exposures to one tenth of the appropriate limit (i.e. for members of the public to a committed effective dose equivalent of 0.5 mSv per year) and that further reductions may only be justified in special circumstances.

51. In setting decontamination targets, the appropriate authority should take into consideration proposed and likely future use of land, plant and materials.

Monitoring

52. It is necessary to derive from the basic objective, using a model where necessary, a value of an easily measured parameter that can be used by both the operator and the appropriate authority to decide when the objective is met. For example while the basic limit on soil activity may be expressed as a number of Bq per gram, it is an advantage to convert this to an equivalent dose rate at a specified distance above the soil surface. It is feasible to carry out dose rate surveys over large areas with a low probability of missing small areas of significance; it is not feasible to take enough soil samples to have the same confidence that no hot spot has been missed.

Clearance of Plant and Equipment

53. During the operation of the mine items may leave the controlled and supervised areas if their surface contamination is less than the levels prescribed in Schedule 8 of the Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (1980). These same standards will apply during decommissioning. However, where a piece of specialised equipment is to be transferred to another mine or mill processing radioactive ores it may not need to be fully decontaminated. Only the outer surfaces will need to be decontaminated or wrapped to ensure compliance with the Code of Practice for the Safe Transport of Radioactive Substances (1982) during transfer from one site to another. The receiving site should have staff competent to deal with contaminated items.

54. Schedule 8 of the Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (1980) refers only to alpha emitters, and is normally interpreted as applying only to 'loose' or 'easily removable' contamination. There will be plant items with high levels of 'fixed' contamination to be dealt with during decommissioning and there may be items where the contamination by beta emitters needs to be taken into

account. In considering fixed contamination, the probability of it remaining 'fixed' must also be considered. If the equipment is likely, for example, to be ground or hammered then it may be appropriate to regard all contamination as potentially 'loose'.

55. Where the interior surfaces of a plant item are likely to be contaminated, that item should be regarded as contaminated unless it can be shown that such interior contamination cannot possibly reach man.

56. Decontamination of plant and equipment to be reused in other than uncontrolled areas should be carried out to the maximum extent possible. Any equipment which cannot be economically decontaminated should be disposed of to a suitable facility such as the tailings impoundment, the mine pit or an appropriate state or federal waste disposal facility (if one exists). Care must be taken that such waste does not reduce the integrity of the disposal site. For example, hollow vessels or timber are unlikely to be acceptable for disposal in the tailings impoundment.

Ground Contamination

57. The acceptable level of ground contamination should be calculated on the basis of:

- dose rate at 1m above ground surface;
- possible use of land to grow food or pasture crops;
- possible impact on or of burrowing animals;
- possible emanation of radioactive gases;
- possible ground or surface water contamination by seepage, runoff and erosion; and
- possible use by man, including recreational use.

58. From these considerations permissible levels of ground contamination should be derived for the top 15 cm of soil. The permissible levels should be calculated to control human exposure well below the limits given in Schedules 1 and 2 of the Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (1980), taking into account expected occupancy and use of the rehabilitated site and its environs. These permissible levels should be converted to parameters that can be simply measured, for example beta-gamma dose rate on the ground surface and/or at 1m above the ground surface. These latter parameters should be used in regulations since they can conveniently be checked by both operator and appropriate authority.

59. Appendix II provides a simplified example of how to calculate a soil concentration limit.

STRATEGY FOR DECOMMISSIONING

60. The objective of decommissioning is to reduce health and safety risks associated with the mine site. Mine workings, mill sites and waste disposal sites should be made safe and health hazards reduced so that the rehabilitation of the site is facilitated. The operational, decommissioning and rehabilitation phases should overlap. For example, tailings impoundments may be progressively decommissioned and rehabilitated during the operational life of a mill. Where this can be done it has the advantage of early stabilisation of tailings and reduction of dispersion of contaminants . It would also provide valuable site specific experience to guide the final rehabilitation of the whole site.

61. Decommissioning should be programmed so that the engineering objectives of rehabilitation are achieved. During decomissioning, erosion and radiological protection should be maintained. The water management system should be operated as authorised in relation to sediment control zones and restricted release zones. All areas should be rehabilitated as soon as possible.

Site Clean-up

62. Site clean-up aims to improve the visual appearance of the area by removal of structures, equipment, rubbish and scattered accumulations of wastes. It can also serve to localise wastes and pollution by the removal of small accumulations of waste or polluted ground to a minimum number of waste disposal areas.

Decommissioning of Machinery and Buildings

63. To facilitate site rehabilitation it will usually be an advantage to remove machinery and buildings from the site. The decontamination of buildings, plant and equipment is discussed in paragraphs 49-59.

64. There will be situations where some machinery is best disposed of in the worked-out mine or the tailings impoundment rather than decontaminated and removed from the site. Care must be taken to ensure that contaminated plant or machinery disposed of in the tailings impoundment does not create voids, is adequately buried and does not cause slumping.

65. Building and plant foundations will also require disposal. Foundations may be covered with a suitable thickness of barren waste rock and soil and revegetated where feasible. Where it is found necessary to remove some or all of the foundation material it could be disposed of in the mine pit or, with suitable care, in the tailings impoundment. In some cases approval may be given for the retention of buildings on the site provided they have been adequately decontaminated.

Decommissioning of Mine Workings

66. Decommissioning and rehabilitation requirements of uranium mines are dependent on the type of mining method selected. The requirements for underground and open cut mines are discussed in this Guideline, whereas the groundwater rehabilitation aspects of in situ leaching operations are discussed in the Guideline: The Mining of Uranium by In Situ Leaching.

Decommissioning of Underground Mines

67. The decommissioning and rehabilitation of underground uranium mines should take into account the following aspects:

- prevention of unauthorised access to mine workings;
- prevention of collapse and resultant surface subsidence;
- restriction of seepage from the mine;
- restriction of release of radon gas from the mine; and
- prevention of surface water flow into the mine.

68. All portals, shaft caps and other openings to the surface should be filled with solid concrete plugs well keyed into fresh rock.

69. The safety precautions utilised for stabilising the roof, walls and floors of underground openings must be designed for the long term where collapse and surface subsidence is possible. Any fill used for the backfilling of voids should be of low permeability. Collapses of abandoned mine workings in the past have led to the creation of pathways into and from the mine workings.

Decommissioning of Open Cut Mines

70. Open cut mines can be excavated into the side of a hill as a quarry cut, below the surface as a pit or a combination of both. The size, shape and wall slope of the open cut depend upon the depth and configuration of the ore body, the cut off ore grade and the rock mechanics of the country rock.

71. In normal practice the design of an open cut mine is determined by the safe, least cost, slopes which provide access to the economic ore. It is designed on the basis of geotechnical investigations carried out before the start of excavation. The major variable in determining the ore to waste ratio is the slope of the open cut walls. This slope is calculated during feasibility studies based on structural data obtained from logging cores and from mapping surface outcrops. These data are usually scanty and subject to reassessment during the development of the open cut.

72. It is important that factors of safety against failure are maintained or increased to ensure safety of a rehabilitated open cut mine over the long term. Reduction of factors of safety may be brought about by weathering, toppling, blasting or changes in groundwater levels etc. Options for increasing factors of safety include flattening slopes, stabilising slopes by drainage or, in special cases, by reinforcement.

73. If the appropriate authority determines that open cut mine slopes may be left as excavated without further treatment there should be an ongoing monitoring program using the most reliable prediction methods, e.g. measurement of slope displacement. If a risk of failure was accepted it would be on the ability to predict and accommodate failure without risk to man or environment.

74. The presence of groundwater and pore pressure has a large influence on the selection of economic slopes which will remain stable over the operational life of the mine. Where pore pressure exists, slope stability may be improved by drilling drainage holes into the slope, rockbolting, meshing or other means. These means are only short life measures appropriate to the operational period of the mine.

75. Open cut mines cannot usually be decommissioned and rehabilitated progressively. This can usually be done only after all economic ore has been removed.

76. Most open cut excavations extend below the regional water table. During the operational period water which: (i) flows in from the groundwater; (ii) is caught in the mine catchment; or (iii) is contributed from outside catchments, is removed by pumping to a storage within the Restricted Release Zone. Once mining ceases and water removal is discontinued, water will fill the pit until a dynamic balance is reached. The level of the lake formed will fluctuate with rainfall, runoff, regional groundwater and seasonal evaporation.

77. Options available for decommissioning and rehabilitating an open cut pit depend on the reactivity of the wall rock, the stability of the walls in the long term, safety considerations, aesthetic values, possible future land uses, and existing drainage patterns. The range of options include one or more of the following:

- leave untouched, in the final excavated form, revegetating to improve aesthetic considerations;
- allow to fill as a permanent water body with overflow provisions where necessary;
- fill with wastes and cover, establishing vegetation;
- rework the benches to provide flatter slopes; and
- blast the walls to form a basin.

78. The transport mechanisms to be allowed for in the final rehabilitated pit include:

- surface water erosion and deposition;

- surface drainage of waters containing contaminants in soluble and particulate forms;

- seepage into and from the groundwater of water containing contaminants;

- gaseous emissions particularly exhalation of radon to the atmosphere and their subsequent dispersion by means such as advection, convection, diffusion, etc;

- wind erosion, transportation and deposition of particulate matter; and

- physical transport by failure of unstable slopes or by anthropogenic operations.

79. Allowance should also be made for possible benefits resulting from the assimilative capacity of natural materials, for example:

- chemical reactions between the waters and soils or rocks may neutralise or buffer groundwaters exchanging contaminating ions for more soluble ions thereby effectively delaying the rate of movement of a pollution front.

- certain clay minerals have an adsorption/desorption capacity which retards the rate and reduces the ultimate extent of the movement of trace elements, effectively locking these undesirable contaminants close to their source;

- vegetation, such as wetland filters, is able to extract trace elements and to change pH, concentrating and immobilising the elements in biologically unavailable forms; and

- weathering of freshly exposed rock surfaces can be most rapid soon after surfaces are exposed but the rate of weathering decreases as the weathering front progresses into the rock mass. Production of contaminants from reactive rocks will thus be greatest during the short term reducing in the long term.

80. Rehabilitation strategies based on extensive research would include such natural processes to "mop up" the residual pollution transport mechanisms which cannot be reduced in the engineered rehabilitation which utilises best practicable technology.

Options for Decommissioning of Open Cut Pits and Quarries

81. **Leave as excavated** - The requirement that open cut excavations remain stable during the life of mining can mean, in some instances, that the pit is also stable in the long term. The safety aspects of the abandoned pit may be the only requirement to be considered at decommissioning for stable mine walls associated with low mineralisation, low radon exhalation and unreactive rock. At a well executed decommissioned mine the abandoned open cut mine may present the major remaining threat to man and animals with potential mortality being much greater than the threats presented by the radiological components. This option is applicable to quarry cuts which can be drained and to open cut pits which lie above the regional water table in climates which are not classified as wet.

82. **Fill open cut pit as a water body** - The prime management option to control the rate of radon exhalation from pores in rocks and soil is the manipulation of the degree of saturation of those pores. If the regional water table lies close to the surface or if the surface drainage pattern leads to or through the location of the open cut, it will be difficult to maintain the open cut in a dry condition and it may be advantageous therefore to allow water to fill the pit, providing a residual resource e.g. a recreational area. The water body so formed would be in dynamic equilibrium with the groundwater level, precipitation, inflow, outflow, and evaporation.

83. As well as assisting in reducing the total rate of exhalation of radon by covering rock surfaces with water, and minimising the depth available for concentration of radon, the provision of a water body which is flushed regularly can have the advantage of maintaining the pH of the water in the pit at a level which is less conducive to the mobilisation of trace elements.

84. Water bodies which are not flushed can concentrate salts by evaporation as well as allowing pH shifts and can thus become a contaminated body, conducive to mobilisation of trace elements and a source of surface water and groundwater pollution.

85. Walls of mines which contain reactive materials such as pyrites can contribute to the pollution load of the water body in the oxidising zone. Reactions which convert the sulphides of pyrites to sulphuric acid can be purely chemical, electro-chemical, or bacterially catalysed and take place at optimum conditions of low pH. The rate of surface reaction is rapid in freshly exposed mineralised material and decreases with time as the reaction front moves deeper into the material. The rate of reaction and thus the rate of generation of acid and contaminants should be minimised to below that rate which can be assimilated by the environment. Options which may exist are the acceleration of the surface weathering processes under controlled conditions e.g. by maintaining pH neutral, and by sealing reactive zones with liners such as well compacted clays, concretes, bituminous concretes etc. Flushing can be a mechanism for providing oxygen to the water body. As mobilisation of trace elements is a function of the potential

for oxidation and the dissolution of ions, the decision whether to flush or not to flush the water body can be dependent on the potential effect of these two processes.

86. The contribution to or from groundwaters may be of concern e.g. in calcareous rocks with interconnected voids or caverns, jointed rock aquifers or porous zones. Liners may be necessary to reduce the hydraulic conductivity of the walls to below that of the surrounding rock. The liner should be conservatively designed and in cases where the hydraulic gradient is towards the pit may have to be covered with supporting and weighting layers using flatter slopes to prevent the lifting off of the liner. The disposal of tailings into the lower levels of the pit may provide a suitable support cover as well as being less permeable than the surrounding rock.

87. **Fill with wastes and cover with vegetation** - In the overall waste management program, wastes such as tailings, bogum, waste rock, etc, may be disposed of by placing in the open cut pit. This method minimises the volume of wastes remaining on the surface. Where progressive disposal of tailings and other wastes into a previously worked-out open cut is possible, below grade disposal and filling of the open cut may be achieved in the same operation. Otherwise, the temporary storage of wastes, in above surface impoundments and dumps may be utilised as part of the waste management plan during the operational phase with subsequent reclamation and final disposal in the open cut. Factors to be considered in decommissioning and rehabilitating open cuts used as disposal sites are discussed in the Guidelines, "Tailings Impoundment for Uranium Mines" and "Waste Rock and Ore Stockpile Management". The material used to back fill the pit will generally be quite porous as the final volume of waste materials to be disposed of may be more than 150% of the original volume excavated. Thus the material remaining on the surface may be more than 50% of the volume of the pit.

88. Water may fill the pores of coarse, porous rock. This water will behave in response to inflows, outflows and changes in groundwater levels in a similar manner to a water body. However, the cover provided by the waste materials will reduce the impact of evaporation on the water balance for the pit. The significance of this is highly site-specific and dependent also on the effectiveness of the cover in controlling infiltration and inflows by runoff from the surrounding catchments.

89. The disposal of reactive wastes deep into the pit surrounded by membranes could be designed to reduce the mechanisms promoting the rate of reactivity and also to reduce the transport mechanisms effecting the rate of dispersion of contaminants to the environment.

90. The evaluation of the impact of the pit water on the surrounding groundwater is important, as the water contained in aquifers which connect with the pit may be of differing qualities. e.g. An investigation in the USA found higher

concentrations of radium in an aquifer caused by ingrowth of radium from uranium previously present in the aquifer; calcrete ore bodies are formed in water which is highly saline; or, ore bodies in features which are pyritic are often associated with naturally acidic groundwaters.

91. **Rework benches to provide flatter slopes** - Safety considerations may dictate that factors of safety against failure of pit walls are not satisfactory in the long term (e.g. a combination of joint orientation, clay filled joints and saturation of wall rocks); or, that factors of safety against accidents occurring under the proposed future land use are not satisfactory. In this event it may be desirable to leave the pit with wall slopes flatter than those considered safe for the short term operational life of the pit.

92. In this case the walls could be reworked to flatten the slopes and dispose of the excavated material into the pit. One method of achieving a safe final pit profile could be the use of a heavy pattern of explosives to shatter the rock of the walls, bulking the rock, and so filling the pit leaving a dished depression underlain by porous rock.

Decommissioning of the Water Management System

93. Decommissioning of the water management system refers to the process by which components of the system are taken out of operation and prepared for rehabilitation. In most mines and mills decommissioning and rehabilitation will be carried out continuously.

94. The constraints which operate during the decommissioning of the water management system and which control the timing and extent of the decommissioning include:

- the degree of contamination of water in the water management system;
- the rate at which complete rehabilitation of the plant site and ore stockpile areas can be achieved so as to exclude these areas from the water management system;
- recognition of the need to have water available on site for rehabilitation works;
- the climate which prevails during the decommissioning and which therefore will control the amount of water lost from the water management system by evaporation;
- the volume of water remaining in storage at the cessation of milling operations; and
- the need to maintain the operation of utilities and access roads around the plant site.

95. The type of water management system used during the mine operation will dictate the methods that might need to be employed in the decommissioning process. These methods would include evaporation of contaminated water, treatment and release of waters with subsequent removal and disposal of the contaminated floor material.

96. Any decommissioning operation should be preceded by a plan which outlines the program of removal of the components of the water management system, the methods to be employed and how the decommissioning of the system will operate under different climatic sequences with appropriate modelling of the water storages being included.

Decommissioning of Tailings Impoundments

97. Following a decision that the operational life of the impoundment is finished, and the deposition of further tailings into the impoundment has ceased, the impoundment should be decommissioned and prepared for the rehabilitation works. These decommissioning activities will include:

- grading the tailings surface to design gradients and levels;
- removal of excess water from the impoundment to an evaporation pond or other means of disposal;
- removal of all pipework and other operating equipment from the impoundment; and
- sufficient time allowed for the tailings to dry such that the tailings surface will support heavy equipment. (During this period it may be necessary to institute dust control measures as the tailings surface dries out.)

98. Where it is proposed to dispose of contaminated machinery and equipment (and other wastes) into the impoundment then this material should be stockpiled. At decommissioning the material should be well buried into the waste. Care should be taken to ensure that such objects do not create voids, are adequately buried and do not result in slumping or detriment to the capping.

99. It must be ensured that adequate supplies of the cover materials are available to complete the rehabilitation works. Where appropriate these materials can be stockpiled ready for use.

100. For a detailed discussion of the rehabilitation of tailings impoundments refer to the Guideline: Tailings Impoundment for Uranium Mines.

Decommissioning of Waste Rock Dumps, Bogum Heaps, Ore Stockpile Areas and Heap Leach Operations

101. For details concerning the decommissioning and rehabilitation of waste rock dumps, bogum heaps and ore stockpile areas refer to the Guideline: Waste Rock and Ore Stockpile Management. Decommissioning and rehabilitation requirements for heap leach operations are discussed in the Guideline: Management of Heap Leach Piles.

STRATEGY FOR REHABILITATION

102. Rehabilitation should not be considered as only that work to be undertaken following the completion of the mining/milling operation. It should be an integral part of the design phase of an operation as decisions taken at this stage will have important implications for the subsequent rehabilitation of a site. In addition rehabilitation should be undertaken progressively throughout the life of the operation wherever practicable (and as required by the Code at Clause 15(1)). Therefore rehabilitation, to be successful, should be considered at all stages of a mining/milling operation.

103. The planning for rehabilitation therefore begins at the conception of the project. The rehabilitation aspects are to be considered in the siting of the mill and associated ponds. The long term effectiveness of the rehabilitation could depend on these initial siting and waste management system decisions. Therefore during the planning and construction phases of the project due recognition should be given to the various elements of the rehabilitation program. It is conceivable that the first stage of progressive rehabilitation will occur during the construction stage. Borrow areas could be shaped and revegetated when no longer required to avoid sedimentation and erosion problems.

104. However, a plan for rehabilitation should be submitted for approval to the appropriate authority before construction commences. A process of continuing review of the rehabilitation program should be undertaken during the operation phase of the project. If a change in mine operations occurs a new rehabilitation plan will be necessary. Implementation of the rehabilitation program is likely to proceed during the operation and post operation phases of the mining project. The rehabilitation phase of the project should include consideration of the predictable long term changes in geological, geomorphological, hydrological and climatological processes. The integrity of the final structures should be such as to survive in the long term (this is discussed in paragraphs 113-117). Wherever practicable rehabilitation should be undertaken progressively throughout the life of the operation (Clauses 5(2) and 15(1)).

Timing of Rehabilitation Planning Proposals

105. Details of the waste management program, including the rehabilitation phase, need to be submitted prior to operation of the mine to the appropriate authority for approval (Clause 5(2)-(7)). Clause 5(7) also states "Prior to the permanent cessation of an operation to which the Code applies, approval shall be obtained from the appropriate authority for the final waste management program, which shall include details of the decommissioning and final rehabilitation phases." It can be seen therefore, that the evolution of a rehabilitation plan occurs throughout the mining operation, with the experience gained from progressive rehabilitation being input into the final rehabilitation plan.

106. Liaison between the operator and the appropriate authority on the rehabilitation plan should occur consistently throughout the life of the operation to ensure that problems of implementation of the final rehabilitation plan and the envisaged land use options of the site are resolved.

Principles of Rehabilitation Design

107. To meet the objectives listed previously the rehabilitation design needs to ensure the containment of tailings, radionuclides, heavy metals and mine and mill products. In the case of tailing impoundments and waste rock dumps, containment is likely to be achieved by the use of soil and rock to protect the materials containing the contaminants from natural erosion forces in the long term, and to control radon exhalation and the emission of gamma radiation. Containment will be further enhanced by rehabilitation of the site to a condition suitable for the designated land use.

108. Therefore the main design principles to be adopted are that the cover:

- be able to withstand natural erosive forces in the long term by:
  - being constructed of selected materials;
  - graded and shaped to avoid erosive velocities; and
  - being able to support and sustain a vegetative cover (if climate allows);

- be of sufficient thickness to control radon exhalation;

- be capable of minimising seepage and rain water percolation through the contaminants and reduce the subsequent dispersal of contaminants by groundwater; and

- be of a design that enables flexibility in selecting land use alternatives post mining.

109. For rehabilitation to be successful continuous consideration should be given during the design and operation of mining and milling works to ensure that best practicable technology is achieved in developing these principles into a rehabilitation program.

Site Specificity and Selection

110. Achievement of the design principles in rehabilitation is dependent on site specificity in relation to economic availability of suitable cover materials, the climate, type of mining and milling processes, choice of waste management system, and the designated land use.

111. The extent of success of a rehabilitation program therefore very much relies upon sound decisions being made in initial selection of waste disposal sites, with regard being given to topography, soil and drainage characteristics of the

area and the designated land use. The success of rehabilitation will depend on trial programs, monitoring and the establishment of reliable and meaningful scientific data banks.

112. A description of site selection procedures relating to specific components of the mining operation are included in the Guidelines: Tailings Impoundment for Uranium Mines; Design and Operation of a Water Management System for a Uranium Mining and Milling Operation; and Waste Rock and Ore Stockpile Management.

Design Life of Structures

113. "Design life" is the period after completion of the rehabilitation works, for which the structure and all its components are expected by the designer to perform fully in accordance with the objectives of the design, on the assumption that no maintenance works are carried out during that period.

114. "Structural life" is the period after completion of the rehabilitation works for which the structure is expected by the designer to perform the functions of the design to a reduced extent. During this time the spread of contaminants would still be at a rate below the assimilative capacity of the overall environment and would not be detrimental to the environment. Conditions in some local areas generally immediately adjacent to the structure may however show the occurrence of detrimental contamination. The "structural life" is therefore a measurement of the useful life of the structure in performance. The structural life can be extended by renovation and maintenance to parts of the overall structure. The design and structural life periods required in this Guideline may serve as a prediction of the periods of effectiveness of the measures taken, but, more importantly, give an indication of the kind of Best Practicable Technology to be used. In this context the objective in the engineering of the waste management structure should be to obtain a design life of around 200 years. This effectively prevents the use of plastics, of exposed steel and probably of any other exposed metal. Use of concrete should be restricted to minor structures, such as for drainage purposes, for which presently it may be the only suitable material available. Concrete design should be mainly directed to durability considerations. Mix design should be such as to obtain maximum density and minimum shrinkage. Special attention should be paid to vibration of the concrete when placed, cement content and fly-ash cement replacement, more than normal cover over the reinforcement, etc. In particular, it requires the use of massive members where concrete is used.

115. A structural life of the order of 1000 years is required where there is to be no effective maintenance. This points to the maximum use of substantial thicknesses of inert soils and rocky materials in the protective works, the design of slopes and their protection, selection of methods and materials to provide erosion resistance, etc. It is necessary to prevent

high velocity water flowing over structures and to incorporate measures in the design to prevent the formation of gullies. It could be expected that care and attention given in the future to such a structure of mainly natural materials would not be less than can be provided by good present day conservation technology. Such conservation measures would prevent extensive gully erosion, by cleaning and repairing drainage structures and channels and giving attention to a vegetation cover when required. It would not include large capital works such as the replacement of cover materials over large areas of the structure.

116. For assessments of the long term structural life of some thousands of years of a waste management structure the effects of good land utilisation and conservation measures may be included.

117. The "design life" of the first vegetative cover in rehabilitation will commonly fall well short of the "design life" of structures. Even with the best practicable technology, the life of the first vegetative cover in the establishment phase cannot be guaranteed beyond three to five years. There will need to be a regular review, every three to five years, of the success of the revegetation program and maintenance requirements. For cases where a native vegetation cover adapted to the local environmental conditions is the long term objective, it can be expected that the stability provided by the vegetative cover will be more durable as the climax community is approached.

Hydrologic Design Criteria

118. To maintain the integrity of the rehabilitated structures, provision should be made in the design for runoff from probable maximum precipitation to be controlled with nil or only minimal effect on the structure. Probable maximum precipitation is based on an assessment of maximum precipitable water contained in a storm. Because of uncertainties in estimating maximum precipitable water it is desirable to calculate a frequency duration curve and compare the runoff from the probable maximum precipitation against a 1 in 10,000 year return period peak runoff. To minimise runoff effect on the structure, flow through rock spillways on the tailings impoundment could be constructed along with armouring of drainage paths. Any drains and flow paths should be designed according to this criteria to minimise erosion effects and subsequent contaminant release. Consideration also needs to be given to flooding by rivers and creeks which could effect the rehabilitated structures thus necessitating that waste disposal structures be sited away from areas that would be inundated by the probable maximum flood.

119. At all times in the design and construction stages of the program of rehabilitation, regard needs to be given to the long term effects of the natural erosive processes that will operate upon the structures.

Engineering Principles for Shaping and Grading

120. The principles employed for shaping and grading of the cover of the tailings impoundment and shaping and covering waste rock heaps are similar in that the aim is to construct a structural cover for the long-term which must resist erosive forces due to water and to a lesser extent wind. Differences can occur in the philosophy of design to the extent whether to let water or not to let water infiltrate into a waste rock dump depending whether it is reactive or not. In arid regions a decision to dish the tailings and retain runoff has advantages in keeping moisture levels up and reducing radon exhalation.

121. The surface of any impoundment cover structure should be graded to ensure that rainfall, in excess of that required to maintain vegetation, runs off, thereby minimising the seepage of rainwater into the tailings. To ensure long-term positive drainage grades, allowance must be made for the settlements which will occur in the tailings when surcharged by the cover structure and for water loss from the tailings by seepage. The quantity of cover fill required can be reduced by grading the surface of the tailings and by using small drainage grades. Grades of the final tailings surface can often be controlled by the placement of the tailings e.g. by suitable beaching methods. Final drainage grades should be between 0.5% and 3% after long term settlements have occurred. However, site specific conditions would determine maximum permissible drainage grades.

122. For impoundments with a finished surface only slightly above grade, the drainage grades should be directed to one or more of the sides. Where the cover surface is well above the adjacent natural surface, such as with a ring dyke, a surface grading to one or more spillways capable of handling design flows should be employed to safeguard the structure. Such spillways are preferably located over lower sections of the outer embankment as relatively wide and thick structures of uniformly graded durable rock fill, allowing the normal discharge of runoff water to flow through the rock fill so that the flow velocities are kept small. The materials selected to construct impoundments and to cover the rehabilitated impoundments should be designated as unreactive. These materials should not contain mineralisation which is (i) "specified material" under the terms of the Code, or (ii) material which has the potential to mobilise trace elements, or (iii) material which will lose its structure under the range of potential influences. Although these materials are unreactive there are possible situations when the most suitable materials available may contribute to the pollution load of the runoff to a greater degree than seepage through the rehabilitated impoundment. In this circumstance and more particularly in arid regions it may be desirable to discourage runoff by forming a dished surface and so reduce the erosion potential of water flowing over or through the banks.

123. Outer slopes of embankments of tailing impoundments should be relatively flat when the rehabilitation work is completed to

minimise the erosion potential. The low permeability clay zones in the embankments may be affected by chemical action with constituents of the tailings seepage water. This also applies to coarse materials in the embankments which will also be subject to natural weathering.

124. Conservative factors of safety are required for long-term embankment stability. The selection of the gradient of the embankment slope will be influenced by the cost of earthmoving, the availability of suitable soil and rock, the erosion resistance of the soil and rainfall intensity. The following table provides a guide to the maximum slope which may be appropriate for different conditions. However, each case should be assessed for specific site conditions.

MAXIMUM EMBANKMENT SLOPE

	Rainfall Intensity/Duration		
	Low	Moderate	High
Soil	≤1:10	⟷	≤1:20
Rock Cover	≤1:5	⟷	≤1:5

Where steeper slopes are proposed an assessment should be given why flatter slopes are considered impracticable and the compensating factors and conditions identified which could make such steeper slopes acceptable.

125. Berms are recommended where uncontrolled flow down batters greater than 5m may result in erosion scours. The following table provides a guide to the vertical spacing between berms.

VERTICAL SPACING BETWEEN BERMS

	Rainfall Intensity/Duration		
	Low	Moderate	High
Maximum Vertical Spacing between Berms (m)	10	⟷	5

126. The berms should be of sufficient width to allow for a berm drain at the toe of the upper batter and for access for plant, equipment and vehicles for rehabilitation and maintenance activities. Generally this should be not less than 3 m. Berms should have a maximum lateral slope of 5% into the toe of the upper batter.

127. The berms should have a longitudinal gradient to facilitate free drainage at non-scour velocities along the berm drain and generally this should not exceed 1%. The berm drains should be protected by rock, concrete or other lining or by establishing a vegetative cover, always ensuring non-erosive velocities.

128. There should always be suitable discharge structures at the end of berm drains to ensure that discharge water does not erode into the batters or surrounding terrain. Runoff can be collected on each berm and directed to lined channels constructed down the batter. However there is some doubt whether such lined channels, with entrance and energy dissipating structures at each berm, can remain effective in the long term without substantial and regular maintenance and repairs. For a detailed discussion of this aspect refer to the Guideline: Waste Rock and Ore Stockpile Management, paragraphs 68 to 84.

Surveillance Procedures

129. The extent to which a rehabilitation program is successful should be ascertained by establishing surveillance procedures. These procedures should include a program of regular inspections to ensure that the rehabilitated structures are performing as indicated in the proposed program. Monitoring of rainfall, streamflows, water quality and erosion rates before, during and after the rehabilitation will provide valuable indications of the effectiveness of the control measures and assist the appropriate authority in developing an adequate maintenance program if needed.

130. Details of the monitoring program to be implemented after rehabilitation should form part of the rehabilitation plan.

DRAINAGE, SEDIMENTATION AND EROSION CONTROL

131. The main factors which influence erosion include the erodibility of the top soil, the topography (steepness and slope lengths), the vegetative cover, the climate, rainfall and wind intensity (related to duration and recurrence interval) and management practices.

132. The severity of erosion problems varies markedly with the type of soils and climate. In low rainfall areas significant erosion can occur if this rainfall occurs in one or two storms with wind erosion occurring during periods of dryness. Drainage design is very important in reducing the erosive forces of water.

133. The methods employed to minimise the effects of the above factors to control erosion can be grouped into four categories:

- structural
- vegetative
- chemical, and
- management methods.

134. **Structural Controls** - Selective grading and shaping is the main measure to control erosion by reducing slope lengths to reduce the velocity of overland flow, thus diminishing its kinetic energy and ability to start soil particles moving. (Techniques of shaping include berms, ditches, slope intercept drains, erosion control banks, benches etc.) A brief discussion of the process of soil erosion mechanisms by water together with the methodology for predicting erosion rates is given in Appendix IV.

135. The use of an armouring layer of rock or rip rap in conjunction with grading and shaping in certain climate regimes will be an appropriate method to enable the erosive forces of wind and water to be kept in abeyance for long periods of time. The life of the armouring layer depends on the rock durability, that is the resistance of the rock material to mechanical and chemical weathering.

136. A brief discussion of the process of soil erosion mechanisms by wind together with the methodology for predicting erosion rates is given in Appendix IV.

137. The design philosophy to be adopted should be to prevent erosion at the source. Some structural control measures serve to remove sediment from water after it has already started to move. However, inevitably some soil scour may occur during construction and the early stages of rehabilitation before the soil surface is stabilised. Therefore, some temporary erosion control structures may be appropriate to slow the velocity of sediment laden water to the extent that the larger sediment particles settle out of suspension.

138. The temporary structures should complement the permanent design works and include sediment traps, check dams (graded

stone, logs, logs and staked hay bales, sand/cement bags, etc) brush barriers, mesh fences, etc. Generally, these structures should be desilted when they are 50 per cent full and be dismantled when the soil surfaces have stabilised.

139. Other structural measures include culverts, chutes, grade stabilisation structures and lined drains which primarily transport water to allow access and utilisation of the site. Large settling and sedimentation ponds trap sediment but need to be adequately maintained to be an effective erosion control measure and hence have limited application for a final rehabilitation measure.

140. **Vegetative Controls** - Methods to prevent or reduce erosion by directly protecting the soil surface include vegetation, mulches and chemical controls. Vegetative controls are a natural and aesthetic means of protecting the soil surface from erosion over the long term. A common vegetative control may include the establishment of an annual and perennial grass and legume ground cover and subsequent establishment of a long lasting shrub and tree cover.

141. **Mulches** - Vegetative mulches can be used to promote rapid germination and establishment of a vegetative cover, and, at the same time, provide temporary protection against surface erosion. Vegetative mulches include straw, woodchips, wood fibre, brush matting, etc. Crushed rock and cement are examples of non-vegetative mulches.

142. **Chemical Controls** - Chemical ameliorants can be sprayed onto soil to protect the surface against erosion during the germination and establishment period for vegetation. Chemical ameliorants include bituminous emulsions, surfactants, etc. They are only a temporary measure to allow vegetation to establish. Dust retardant chemicals are also very useful in dry areas where wind erosion is a problem.

143. **Management Methods** - The proper sequencing and location of the various erosion control measures during construction and operation is critical to the successful control of erosion and sedimentation. In carrying out rehabilitation the basic fundamentals of maintaining non-erosive velocities in flowing water and establishing vegetation to protect the soil surface need to be observed to ensure clean runoff.

144. Drainage works may be necessary to divert surface water flows around various sites in the project area to avoid failures of rehabilitated structures such as tailings impoundments and waste rock dumps. Channels and banks can be protected against erosion by rip rap but if at all possible the grades should be such as to prevent erosive velocities in the channels.

Management of Drainage Works by Owner/Operator/Manager

145. During the owner/operator/manager's period of responsibility, site inspections by a surveillance committee

convened by the appropriate authority and including a representative of the owner/operator/manager, should be conducted to ensure that the program of rehabilitation works is working successfully. Any failures in the integrity of the cover should be reported, reasons for such failures determined and repairs carried out immediately. The consequences of any perturbation to the vegetation cover such as fire, insect infestation, overgrazing etc should be closely monitored to detect any increases in soil erosion that may occur on the site. In particular, repairs and maintenance works should be carried out to avoid failure of the cover and subsequent possible release of tailings and other contaminants to the environment.

ASSESSMENT OF POTENTIAL GROUNDWATER CONTAMINATION BY SEEPAGE FROM REHABILITATED WASTE DISPOSAL SITES

146. The Code requires that release of radioactive wastes not controlled by the formulation of discharge limits be minimised by the use of best practicable technology and be acceptable to the appropriate authority (Clause 7(4)). This requires that uranium mining and milling wastes be disposed of in a manner which minimises, over the long term, the potential for dispersion into the environment of the radiological and non-radiological contaminants in the wastes.

147. Disposal will usually involve containing the wastes in structures composed of inert materials such as rock and soil. For the period that the structures continue to act effectively as designed, the erosive forces of wind and water will continue to be adequately controlled. However, water will be able to pass through the interconnected pores in the matrix of the structure and in the contained wastes. This is potentially the critical pathway by which contaminants may be dispersed to the environment from a rehabilitated disposal site. The owner/operator/manager will therefore need to demonstrate to the satisfaction of the appropriate authority that the rate of dispersion of contaminants from a rehabilitated site, via the seepage pathway, has been minimised by the use of best practicable technology and will be such as to have no deleterious effect on the environment. This will involve the determination of predicted seepage rates from the disposal site, the estimated contaminant load of such seepage, and the effect of the contaminants on the environment.

148. The passage of water through a disposal site does not necessarily mean contaminants will be dispersed to the environment at a rate which gives cause for concern. A knowledge of the operative chemical relationships is required to appreciate the potential for dispersion of contaminants, and this information needs to be considered in conjunction with the predicted rates of movement of water through the disposal site. The chemical relationships depend on: the contaminants present in the wastes; chemical leaching; subsequent oxidation/reduction; dissolution/precipitation; and sorptive reactions that occur as the contaminated water moves through the pores and interacts with the matrix material. The contaminant transport/retention relationship is therefore extremely complex and requires considerable investigation in the field and in the laboratory to determine chemical characteristics.

149. It is also necessary to minimise seepage in order to ensure the structural integrity of waste disposal facilities. Excessive saturation, seepage forces and uplift pressures can all lead to structural failures and would have been taken into account in the design, construction and operation of the waste disposal facilities. However, the site of the facility and the design of the structure are also key components in ensuring that seepage is minimised over the long term. More information on containment structures is contained in the following Guidelines:

- Tailings Impoundment for Uranium Mines;

- Design and Operation of a Water Management System for a Uranium Mining and Milling Operation;

- Ore Stockpile and Waste Rock Management; and

- Management of Heap Leach Piles.

Factors Determining Contamination Potential of Seepage

150. The factors which determine the groundwater contamination potential of tailings seepage include the following:

- the net infiltration of precipitation into the rehabilitated tailings disposal system which will determine long-term leaching of soluble tailings contaminants

- the location, flow rate and chemistry of the groundwater

- the chemical composition of the tailings

- the geochemical characteristics of the soils and bedrock underlying the tailings disposal system.

151. These factors are obviously site specific and the extent to which each influences the contamination potential is related to whether (i) the tailings are located at a "dry" (arid) site or a "wet" (humid) site, (ii) the water table is relatively deep or shallow (iii) the milling process involves an acid or carbonate leach (iv) the tailings are neutralised prior to disposal (v) the tailings disposal system is above or below grade and lined with a low permeability medium.

Measuring and Monitoring Seepage

152. Seepage is not amenable to direct observation so it is difficult to measure and monitor. Most methods require the development of mathematical models having characteristic parameters which may be observed and related to the model and thus allow a "seepage estimate" to be calculated. It should be noted that the errors associated with this process may be quite large when compared with the actual seepage.

153. The most common method of indirectly measuring seepage through dam structures and foundations is to construct a series of observation points downstream of the dam. The use of piezometers allows observations to be targeted for differing levels as well as differing locations, and to be highly responsive to fluctuations in the piezometric surface. The peizometric surface can be estimated from field determinations and applied to the mathematical model to calculate estimates of seepage through the foundations. Tracer methods may be used to determine seepage pathways.

154. The water balance method requires measurements, or modelling of the components listed in the following table:

COMPONENTS CONTROLLING GROUNDWATER FLOW

Parameter	Component
Input	Infiltration (I)
Output	Evapotranspiration (ET) Extraction from Groundwater Storage (P) Interflow within the Unsaturated Zone (U) Baseflow from the Saturated Zone (S)
Storage	Unsaturated Moisture Storage (US) Saturated Groundwater Storage (SS)

The water balance method is illustrated in Appendix III.

Quantitative Modelling Techniques for Contaminant Transport

155. The quantitative modelling techniques for contaminant transport from mill tailings are similar in many ways to those applicable to other types of contaminant migration situations such as the shallow-land burial of low level radioactive wastes. However the complex chemistry of mill tailings and geochemical processes including neutralization of leachate by soils and bedrock along the transport pathway complicate the modelling procedure for mill tailing sites. Typical linear equilibrium concepts such as the retardation factor and distribution coefficient may not be appropriate for modelling of mill tailing sites where high ionic concentrations and low pH may make the interaction of the dissolved radionuclides with the soil or rock highly non-linear and time dependent (ie non-equilibrium conditions). Unsaturated flow in some of the tailing disposal site settings and the transient existence of the milling operations may present special modelling problems. Non-radioactive contaminants such as selenium and sulphates are often a greater problem than radioactive contaminants. It is only very recently that computer codes specifically aimed at modelling groundwater contaminant transport from mill tailing sites have started to be developed.

Collection of Data for Predictive Modelling

156. All parameters used to predict the migration of radionuclides and other contaminants should ideally be obtained from field tests conducted at the site being investigated and laboratory investigations of the site materials. The field program carried out should provide a sound understanding of the hydrogeology, hydrology and baseline ground and surface water quality of the site.

PARAMETERS USED TO PREDICT THE MIGRATION OF A RADIONUCLIDE IN A MINE WASTE DISPOSAL SITE

Parameter	Technique of Evaluation
Piezometer Head	Field investigations obtained from reading plezometers
Hydraulic Conductivity (permeability)	Field or Laboratory (permeability testing)
Saturated Thickness of Aquifer	Field investigation (explorations)
Velocity	Calculated from the equation
Distribution Coefficient	Laboratory
Effective Porosity	Laboratory
Bulk Density of Medium	Laboratory
Equilibrium Constant	Equation
Longitudinal Dispersivity	Field or laboratory tests
Transverse Dispersivity	Field or laboratory tests
x - Component of Dispersion Coefficient	Equation
y - Component of Dispersion Coefficient	Equation
Decay Constant	Literature
Modecular Diffusion Coefficient	Literature or Laboratory test
Present Concentration of a Radionuclide or Solution	Laboratory test

Rehabilitation Measures For Controlling Seepage

157. Figure 2 provides a schematic representation of the hydrologic cycle compartmentalised to show the groundwater flow. The control of seepage depends on the factors presented in the above Table. Short term benefits may be achieved by controlling any one of the factors but in the long term the change in storage is small (fluctuating around zero). Therefore inputs are equal to outputs. This can be represented by the following equation:

$I = ET + P + U + S + \Delta SS + \Delta SS$
when $\Delta US + \Delta SS = 0$ over the long term
and $U + SS$ = seepage = $I - ET - P$
seepage can be minimised by minimising
$I - ET - P$

158. During the operational stage active management measures would involve extraction of water from the saturated zone for return to the mill cycle or for disposal by evaporation. If extraction (P) is large enough for the expression I - ET - P to be negative, then seepage would be negative i.e. no loss from the impoundment. In the post operational phase, without active management, P = 0 and seepage can be minimised by minimising I - ET. It should be noted that the methods available for minimising total seepage are related solely to the surface where infiltration can be minimised and evapotranspiration can be maximised.

159. In order to minimise infiltration (I) the volume of overland flow from the site must be maximised and the evaporation from above the surface maximised. The methods available for this are good drainage design combined with impermeable cover zones. Provision of piped drainage within a pore breaking zone of a cover, above an impermeable zone, may marginally assist drainage.

160. In order to maximise evapotranspiration (ET) water must be available for evaporation, on the surface, or for transpiration, in readily available soil moisture storage within the root zone.

161. The methods available are treatments to minimise permeability upstream of retaining structures and/or adequate vigorous vegetation growth in soils with more than adequate soil moisture storage.

REVEGETATION

162. Rehabilitation proposals should carefully consider whether the provision of a vegetative cover would serve a useful purpose and is the most appropriate stabilising cover in the long term.

163. While most of Australia has a vegetative cover, large areas of the arid environment are only sparsely vegetated and some lack any vegetative cover. In such areas, vegetation may fail as a permanent cover. In some areas vegetation is concentrated into special micro-environments.

164. The objective of a vegetation cover is to provide protection against wind and/or water erosion and to provide a significant component in the water balance, while at the same time restoring the aesthetic appearance of the site. Site specific assessments are needed, based on rainfall quantity and intensity, temperature, radiation, evapotranspiration, landform, soil type, etc to determine whether a vegetative cover is most appropriate or not.

165. Where a self-sustaining vegetative cover cannot be maintained in the semi-arid or arid environment, other armouring strategies may be needed against wind and possible water erosion. (See Figure 1 of the Guideline: Tailings Impoundment for Uranium Mines).

166. Erosion reduction by vegetation is directly related to the amount of plant material, living and dead, both above and below the soil surface. Stems, leaves and plant shoots intercept rainfall and thereby reduce the force of impact at the soil surface. Plants and the litter cover they produce obstruct runoff, increase the moisture-holding capacity of soil, enhance infiltration, prolong evapotranspiration, reduce the accumulation of runoff into sediment-bearing streams, and slow existing streams so their load of silt and litter is dropped. Similarly, above-ground parts of vegetation and rock material increase surface roughness and reduce wind velocity, decreasing its ability to initiate or maintain soil particle suspension. See Appendix IV: Processes and Estimation of Soil Erosion.

167. The actual amount of vegetation cover required for adequate erosion protection depends on several factors including:

- the amount and intensity of rainfall;
- the wind velocity and direction;
- length and angle of the slope to be stabilised;
- erodibility of the site-specific soils; and
- aspect of site.

168. While revegetation may be useful for short-term stabilisation, a number of uncertainties lessen its attractiveness as a long-term strategy including:

- difficulties with initial establishment;
- reliance on maintenance (such as irrigation, fertilisation, etc);
- the invasion of newly established communities by a few aggressive early successional plants should be accepted for the value they will have in many situations in promoting early stabilisation. Even weeds (noxious weeds excepted) may be useful for this early stabilisation phase;
- infrequent but catastrophic events (e.g. massive floods, windstorms, fires and insect or disease outbreaks); and
- effects of long-term climatic trends.

169. The factors that determine the success of revegetation can be generalised as requiring an understanding of local climate, vegetation, soils and topography. Current knowledge suggests that the maximum possible cover that can be expected from revegetation can be estimated by surveying existing undisturbed (uncleared and ungrazed) natural vegetation. It is unlikely that any greater cover can be sustained over the long-term with minimal maintenance than that appearing in natural communities. On this basis, revegetation of project areas located in areas supporting desert vegetation may offer little erosion control on unstable surfaces. The following diagram is a simplified representation of the decisions which need to be made in this regard.

Erosion Control - Revegetation or Other Armouring Strategies

Revegetation	Armouring Strategies
. effectiveness and practicability	. erosion control potential
. soil suitability	. slope stability
. slope	. aesthetics
. availability of appropriate species	. composition
. cultural practices	. availability of materials
. stability and resilience	. durability of materials
	. bedding material

170. The revegetation program for a mine project area is complex and needs to take account of the vegetative cover required to control erosion at any one site in the project area, as well as the different substrates on which it is proposed to establish vegetation. These substrates include topsoil, soils from lower horizons, weathered rock and waste rock.

171. There is considerable confusion over the term "topsoil". A generalised soil profile can be described as follows:

Surface (A1) horizon	Dark; organic-rich; accumulation of plant nutrients and seeds; main root zone; generally lighter texture.
Subsurface (A2) horizon	Pale; lower in organic matter and nutrients than A1; limited root penetration;
Subsoil (B) horizon	Strong colour; low in organic matter and nutrients; limited root penetration; possible accumulation of salts; generally heavier texture than horizons above.

172. Topsoil in most areas is usually considered to be the A1 horizon, although in some areas where the A1 horizon is relatively thin, it can include some or all of the A2 horizon. The B horizon is rarely considered suitable for topsoil, except in those instances where its physical and chemical characteristics are assessed as suitable for seed germination and plant growth.

173. For revegetation purposes, the "topsoil" can be defined in a number of ways as follows. The appropriate description will depend on the site conditions.

Topsoil is:

- the dark, organic-rich surface soil comprising the main root zone (down to 100-200 mm, say), or
- a minimum 100 mm (say) of surface soil, or
- a more specific description defined by physical and chemical testing.

174. Topsoil provides a good medium for germination, establishment and growth of vegetation, as well as containing organic material and seeds, and is thus of prime importance in the long term stabilisation of land surfaces by vegetation.

175. Any revegetation program in the mine project area almost invariably involves covering the site with a layer of non-toxic topsoil in order to establish plant growth and control erosion. The thickness of the soil cover required will vary from one mine to another and from site to site within a particular mine project area. For example the amount of soil cover required for a tailings impoundment or waste rock dump has a significant effect on reclamation costs. If too little cover is specified, long-term pollution could result, but if too thick a cover is specified, the costs are unnecessarily high.

176. If the tailings are acid producing, infiltration of surface water into the tailings mass becomes a major consideration. Theoretically, if a clay type cover zone is

perfectly intact, properly sloped and compacted, it could be relatively thin and little infiltration would occur. The problem is that thin soil cover zones never form perfect seals. They are constantly exposed to weather changes (freeze-thaw, wet-dry), mechanical damage (ploughing, vehicular traffic, animal tracks, minor erosion) and plant root activity. All these factors tend to reduce the effectiveness of thin soil cover zones in minimising surface water infiltration. Consequently conservatively thick clay soil zones or clay zones covered with a lighter textured soil cover capable of self healing and accommodating differential settlements etc, should be used.

177. The plant growing medium should be of sufficient thickness to promote acceptable growth, be relatively erosion resistant (i.e. could include a rock soil mixture) and minimise the escape of pollutants.

178. Revegetation is, therefore, a specialised field in itself. Selection of the most suitable plant species and seeding rates, establishment techniques, fertiliser types and application rates, and maintenance procedures requires the guidance of personnel with expertise in this field. Without such guidance, much money and effort can be wasted - applying intensive, high cost treatments where a less intensive and cheaper approach may suffice, or applying techniques incorrectly, or selecting the wrong species or fertiliser, with the result that plant establishment is poor. It is emphasised that, to ensure the success of a revegetation program, advice should be sought from competent experts for recommendations which will be suited to the particular locality and the specific site requirements. Local knowledge could be important in this respect.

Planning for Revegetation

179. The planning for revegetation begins at the conception of the project. Revegetation aspects should be considered in the siting of the project facilities and during the construction phase. The successful revegetation of the site will depend to a large degree on decisions taken at this time. During the siting and construction phases the following principles should be followed:

- Destruction of vegetation and the disturbance of soil should be restricted to the minimum required for site development. The movement of equipment should be controlled to assist this aim. Trees which are to be retained should have a buffer zone retained around them within which disturbance, including compaction of the surface by vehicular movement or stockpiling of material, is not permitted. The buffer zone should be of sufficient width to protect the particular trees being retained.

- In areas of dense grass or herb vegetation it may be helpful, before stripping topsoil, to reduce the vegetation cover by grazing, burning or mowing (preferably with the removal of mown material), as excessive vegetative growth makes topsoil removal difficult. Alternatively, the plant cover may be mulched for spreading on the rehabilitation areas after seeding and fertilising. Unless used for mulch, grazing is the preferred approach for the removal of the vegetation cover as it allows for better retention of seed and vegetative parts from which plants can re-establish. However, in many situations burning may often be a more practical approach, even though it destroys much of the residual seed (although root stock material usually survives).

- In most circumstances clear-felling of woody vegetation involves use of bulldozers and root rakes. The timber is then wind-rowed and, after sufficient drying time, burnt. Stockpiling of such timber rather than burning may prove a greater environmental hazard and encourage fauna to use the stockpiles as habitats - thus bringing fauna into close proximity to operational disposal sites.

- Where burning of the cleared and grubbed debris is permitted, approval should be obtained from the appropriate authority before such operations start.

- Where topsoil is to be retained as a source of seed for future revegetation, additional damp debris or green organic matter should not be added to the topsoil. The presence of large quantities of moist or green material may initiate processes in the stockpile which can reduce the viability of seed.

- The retention of topsoil as a seed source is only effective for a limited period, depending on the moisture and temperature conditions in the stockpile and the type of seed. Hard seed (e.g. wattles and some legumes such as sub-clover, siratro) are less affected by unfavourable conditions in the stockpile than seeds with a softer coat. Most other seed within stockpiles loses viability after four to six months.

- Sufficient suitable soils from under and within the tailings impoundment should be removed and stockpiled for future use in reclamation, unless steep terrain or other considerations make this impractical or if by removal the permeability of the foundations is increased unacceptably.

- To ensure maximum preservation of plant material for revegetation, and to minimise subsoil inversion, topsoil should be removed in two parts. The organic layer is removed and stockpiled first. This stockpile should be a low flat mound, if the aim is to ensure maximum survival of vegetative material (runners, root-stock, etc) or a higher mound, if seed viability is the primary consideration. The remaining topsoil should be removed subsequently and stockpiled in a separate mound. It is recognised that in many regions soils are of such poor quality both physically and chemically that there is no advantage in separating the topsoil into layers. Often topsoil is very shallow and it is impossible to separate layers especially in sandy soils in arid regions. (Soil retention and management are discussed in more detail in Appendix V).

- The stockpiles should be protected from traffic and should be located away from drainage areas. Topsoil stockpiles and disturbed areas that are a potential source of dust or sediment should be stabilised with vegetation, where possible, even if only for a short period.

Research

180. Research may be necessary to determine revegetation requirements. Such research should consider which of the following are necessary for the specific site:

- physical and chemical characteristics of the available soil cover materials (including topsoil, subsoil, weathered overburden rock, etc);

- review of climatic records to determine sowing times, moisture (irrigation) requirements, etc;

- soil temperature trials;

- plot trials to select suitable soils for germination, establishment and long term growth, this may include assessment of vegetative growth on various modified soil profiles;

- research into local native pasture and tree species especially methods of harvesting/collection and applicability in final revegetation program;

- species selection trials and species mixture trials;

- fertiliser trials to determine optimum fertiliser requirements;

- field experiments on site.

The minimum lead time for such work is commonly two years.

181. It should be appreciated that natural soils in the vicinity of ore bodies can have a much higher content of some elements due to weathering of the ore. On these soils only a small increase in the concentration of a particular element may render the soil toxic to vegetation. In addition to direct toxicity effects, the presence of some elements may upset the plant's nutrient supply, so that it exhibits symptoms of deficiency in some other nutrient. For example, high exchangeable aluminium levels "lock up" phosphorous in the soil and prevent uptake by plants. Similarly, high magnesium levels

inhibit the uptake of potassium and a severe excess of magnesium over calcium causes the former to be toxic, even at low concentrations.

182. Isolation of the cause of the toxicity will usually involve separate analyses of soil and plant samples, for anomalous concentrations of heavy metals. Most mines have records of analyses carried out as part of their exploration work. However, these generally involve a complete digestion of the samples and are not representative of plant growing conditions. It is thus preferable to collect fresh samples and analyse for extractable amounts of heavy metals by appropriate techniques.

183. Appendix V provides further information on what research may be necessary.

Site Preparation

184. The following processes and techniques are identified as part of the strategy for site preparation aimed at revegetation:

- surfaces should be shaped, if appropriate, to define the surface drainage system;

- surfaces should be contour ploughed or ripped, if necessary, to break up compacted areas; and

- the surface should be stabilised using a vegetative cover established by seeding and fertilising. The seeds should include some or all of the following:

  - temporary ground cover: seed to provide fast initial germination and establishment of a stabilising cover to act as a cover crop for slower growing species - may include cereals such as ryecorn, oats, millet, dwarf sorghum, annual grasses and legumes.

  - permanent ground cover: seed of perennial grasses and legumes or other low growing herb species, to promote long term ground cover to stabilise the soil surface - primary plants with nitrogen fixing capabilities (e.g. legumes) will improve soil nitrogen status.

185. If the designated land use is sown pasture then seeding stops at this point. If native vegetation is required, then further seeding is necessary:

- Pioneer native species: seed of native species which are considered as pioneer species, adaptable to establishing on disturbed sites (e.g. wattles).

- Climax vegetation species: seed of tertiary species in adjacent climax vegetation communities to add a dimension of time to the planting. Tubestock of these species may be more appropriate. Planting of tertiary species with deep rooting characteristics directly on a tailings impoundment may be inappropriate because roots may penetrate the clay seal zone and allow moisture infiltration and/or release of pollutants.

186. The seed mix should then form the bank for longer term vegetative development, selectively developing on the climatic and management conditions available over time. Additional planting could be concentrated in more critical areas.

Developing a Seed Bed

187. Subsidence of topsoil could be a problem where the surface to be revegetated contains large voids between rocks. For example, waste rock dumps will contain large rocks and topsoil subsidence is likely, necessitating re-grading of the surface and thus effecting revegetation. To avoid this problem, the surface should be kept free of all large objects and should be processed to form a zone complying with the filter criteria to retain the soil particles on the surface.

188. There is no substitute for good quality topsoil to promote a vegetative cover and reduce erosion hazard. However, it seems to be a feature of most mines that they are located in areas of poor quality soils with a thin relatively infertile "A" horizon. Thus topsoil is usually in short supply and the mining company and appropriate authority should be aware of the need to conserve and stockpile it for later re-use. Appendix V gives an outline of those items to be taken into account in the management of topsoil.

189. Wherever possible, sufficient topsoil (as defined in paragraph 167) should be made available to allow a complete cover of all areas to be revegetated. In some instances, such as on a tailings impoundment with a clay seal cover, spreading of topsoil laden with seed of tertiary, deep rooting species, may not be appropriate because of the potential damage to the clay seal from penetration by tree and shrub roots. Where sufficient topsoil is not available or appropriate, a suitable soil should be selected from stockpiles or borrow areas as the surface cover.

190. Prior to topdressing, the surface layer (but not clay seal sub-soil) should be contour ripped or chisel ploughed to a minimum depth of approximately 300 mm. This ripping provides the key for topsoil and improves infiltration of water in the growing zones. It also aids root penetration and improves plant growth and persistence. Contour ripping for several seasons can result in rapid soil improvement.

191. Wastes can become acidic due to the oxidation of sulphide minerals resulting in the generation of sulphuric acid. In cases where the acidity is due to breakdown of unstable minerals, a continuing maintenance program of liming may be necessary for many years, until all sulphides in the root zone have been consumed and the acid neutralised. In addition,

newly placed soil may be inadvertently contaminated with toxic tailings or waste material brought in by plant, vehicles or personnel, necessitating remedial treatment.

192. Assessment of characteristics such as acidity (pH), salinity (EC), and toxic heavy elements (Al, Mn, Cu) should be undertaken before topsoil is spread and seed and fertiliser are applied. Where necessary, amelioration of toxic conditions may be required.

193. Where lime is required, it should be spread and ripped into the top 300 mm of soil prior to topsoiling. At least six weeks should elapse between liming and sowing to allow the lime to react with the soil. Otherwise, it could reduce the effectiveness of fertilisers and affect seed germination. Liming rates are best determined by laboratory and site investigations.

Planting Techniques for Primary Species

194. The most important requirement in revegetation is to rapidly establish a dense, vigorous and persistent vegetative sward, which will stabilise the soil surface with minimum (or low) maintenance requirements. Natural succession through invasion from surrounding areas should also be encouraged.

195. Primary species normally comprise high quality exotic grasses and legumes to suit the particular location. This exotic complex provides a microenvironment for adjacent, localised native grasses, legumes and herbs to invade the area. The rate of plant invasion can be assisted with native seed collection and sowing, as these species offer the greatest potential for long term stability of the ecosystem.

196. A deep rough multi-purpose seedbed is best for revegetation of waste disposal sites. On the slopes that permit, seed and fertiliser can be broadcast or drilled and covered to assist germination. Cultivation should be along a contour to delay runoff, increase water infiltration into the growing zone and control erosion.

197. On steeper slopes sprigging and sodding techniques or hand broadcasting of seed and raking may be used. Site investigation is required to determine the best techniques for revegetation for individual mining sites.

198. Specialised and intensive techniques such as intensive planting, hydroseeding and hay mulching can be used to establish vegetation. These techniques are generally more expensive but promote a more rapid establishment of a vegetative cover, which is particularly important on erosion prone areas, such as steep slopes or drainage areas.

199. Vegetative propagation of a ground cover can be achieved by intensive planting of sod, root or stem material which can be used in a half metre grid pattern into deeply ripped moist

soil conditions. Consideration must be given to ground cover protection and the optimum growing period of species. Sod, root and stems may also be planted in conjunction with seed and fertiliser. Sodding requires less site preparation. In steep critical areas mesh pegging may be necessary to support the sod/plant complex. A slow release fertiliser can be applied with each sod to stimulate growth. Sods should be irrigated until adequately established.

200. Mulching is a technique of applying a material to the surface to improve the microclimate for plant growth. A range of natural and manufactured material has been used but only a few combinations are discussed here. Site investigations are required with these various products and/or their combinations prior to application. Mulching can also afford temporary erosion protection to the soil surface, but there should also be drainage control above the treatment to prevent the mulch being washed away by overland water flows.

201. **Hay and Bitumen Mulching** - Hay mulching has been widely used in Australia as it promotes moisture retention for rapid germination and establishment and provides a degree of erosion control while the vegetative cover is establishing. This technique is recommended for hot, dry environments where seed placed onto dry soil must wait for natural rainfall for germination. It is especially effective on steep slopes where soil moisture may limit plant establishment and growth.

202. The hay should be dry and have a high stalk/low leaf content and should be spread loosely and evenly over the surface at rates of 3-4 tonnes/ha for cool season sowings and up to 10 tonnes/ha in dry hot situations. When placed, the hay mulch should lie firmly on the soil surface and be "tacked" together by a binding agent or, in critical areas, held down by netting. If netting is used, it should be a biodegradable synthetic material or ungalvanised wire mesh. The most widely used binding agent is bituminous emulsion, applied by high pressure spray with the hay or directly onto the land spread hay surface. A slow breaking, non-ionic bituminous emulsion is preferred. Wood shavings, wood pulp and paper pulp can also be used as a substitute to hay, and liquid stabilisers are available as a substitute to bitumen. If this technique is used additional fertiliser may be required. Watering of the seed/fertiliser and protective mulch will improve germination and stimulate early growth.

203. **Hydroseeding** - A hydroseeder can be used to spray a slurry of seed and fertiliser under high pressure onto the area to be revegetated. It is particularly effective on steep slopes. Wood pulp in the slurry acts as a carrier of the seed and fertiliser and sticks it to the surface. This technique is most effective with moist soil or where irrigation is to be used. It is not recommended under natural rainfall conditions in hot and/or dry environments.

204. **Hydromulching** - Seed and fertiliser are applied to the surface and a wood pulp or paper mulch sprayed onto the surface using a hydromulcher. Application rates of 2-3 tonnes/ha have proved satisfactory.

Planting Techniques, Secondary and Tertiary Species

205. Seed of native trees and shrubs can be direct drilled or broadcast over a site. In addition, seed of local species, including grasses and herbs, can be introduced with seed laden topsoil, freshly won from adjacent natural areas. This topsoil can be spread thinly over selected small areas around the site and so become the seed source for later spread of native species. Potential top soil sites can include fire-breaks, haul roads and borrow areas, providing successful revegetation of these areas at a later stage is not hampered by lack of topsoil.

206. Secondary and tertiary species may not be appropriate on tailings impoundments, or other structures with a zoned cover consisting of thin upper layers as root systems may penetrate the cover material. For a self sustaining vegetation, which will require little active management for the long term, the design of the zoned cover must take into account the natural establishment of species other than the primary species. The primary species will inevitably form a component of the self sustaining vegetation regardless of the species initially established.

207. As the artificially formed cover structure is not a natural system, efforts should be made to design the zoning to approximate a natural system in the upper layers. Nevertheless, in spite of such design, the selection of the vegetation type and the subsequent progression to self sustaining vegetation may require consideration of plant types which are not natural to the site prior to disturbance.

208. A native seed collection campaign should be carried out. Collection time will vary with the species, the region and the season. The choice of grasses and small herbs tends to be non-selective, whilst larger shrubs and grasses should be chosen on the basis of their ease of germination and expected survival.

Management of Revegetated Areas

209. Management of revegetated areas will be necessary, though the maintenance requirement will vary considerably depending on the intended land use and time. In all cases, the maintenance objective should be to maintain sufficient vegetative cover for long term stability of the soil surface.

210. If the area is used for grazing there will need to be regular maintenance to maintain a persistent, productive grass/legume sward. If the area is to revert to a local modified climax vegetation, the maintenance requirements will depend on the stage which has been reached in the succession, but should be minimal.

The management program should address such issues as:

- reseeding and new seeding
- fertiliser application
- fire management
- irrigation requirements
- fencing
- mowing
- weed control

211. **Reseeding and New Seeding** - Inevitably some areas will require reseeding where seed has failed to germinate or vegetation has not persisted due to: erosion, compaction, or contamination by acid or toxic metals. Alternatively, with changes in the management approach, etc, additional seeding of secondary and tertiary species may be appropriate to speed up the succession to a climax community.

212. **Fertiliser Application** - Where the vegetation community would appear to require maintenance fertiliser applications for long term stability, a number of issues require assessment, including:

- major, minor, trace elements
- rates
- timing
- application techniques
- tolerance of native species to particular fertilisers, such as phosphorus.

These issues are best assessed by site and laboratory investigations.

213. **Fire Management** - The effect of fires can be disastrous in the early stages of a revegetation program. Protection measures such as fire-breaks and selection of relatively fire resistant species should be used. Many primary exotic species are severely affected by fire, necessitating reseeding of those areas. Native tree and shrub species vary in their adaptability to fire, but generally they are susceptible to damage as seedlings and more resistant as mature trees or shrubs. However, the effect of fire on some native communities can enhance seed germination and in other circumstances destroy potential seed sources. As time progresses, fire should be seen as a natural influence on the succession to a climax community.

214. **Irrigation Requirements** - As noted previously the most important requirement in revegetation is to rapidly establish a dense, vigorous vegetation on the site. To achieve this objective it may be necessary to make provision for irrigation in the early stages to promote rapid seed germination and plant establishment during times of moisture stress, particularly on critical erosion prone areas such as steep slopes or drainage areas. For these critical areas, irrigation can complement a mulching treatment, previously described. The type of irrigation system designed will depend on the quality and

quantity of surface and/or groundwater availability. For example, a drip system may be used for shrubs and trees surrounding the tailings impoundment and a spray system on the tailings impoundment itself. However, it should be noted that plant communities established by irrigation may not survive once irrigation is stopped. Moreover, because irrigation with poor quality water may increase salt accumulation, especially in arid regions, minimum standards for water quality should be established.

215. **Need for Fencing** - It may be necessary to provide fencing on revegetated areas, at least in the short term, to allow the vegetation to become established before being subject to grazing etc by native, domestic or feral animals. The type of fence used is site specific.

216. **Mowing** - Mowing or slashing of young grass/legume swards during the first growing season promotes a sprawling habit which provides greater vegetative cover over the surface. Where secondary and tertiary trees and shrubs are growing in the sward, mowing may not be appropriate if the growing tips are lopped off. However, height of mowing/slashing can be varied to avoid such effects. Mowing of tall, standing herbage at the end of the growing season will also reduce the fire hazard.

217. **Weed Control** - In most areas, there are statutory requirements to eradicate declared noxious weeds. Other undesirable weeds, which compete with the preferred species for moisture, nutrients and light, may also need to be controlled. Weed control techniques must be carefully assessed to ensure that preferred species are not damaged or killed. Broad acre spraying of weeds is not favoured. Hay used for mulch should be rejected if it contains excessive quantities of weed seed. Topsoil should not be won from borrow areas which are heavily infested with weeds.

MONITORING

218. The Code requires the development, approval and implementation of a monitoring program including a post-operational monitoring program (Clauses 5(6) and 14). Through such programs the appropriate authority should be able to assess compliance by the owner, operator and manager with the requirements applied to the particular rehabilitated site. Thus monitoring is an essential element in the decommissioning and rehabilitation program. In this context the monitoring program would encompass area and personal monitoring, direct and remote sampling as well as site inspection and assessment.

219. The overall requirement for rehabilitation is the minimisation of detriment to the environment by the rehabilitated site in the long term, ideally relying on passive (natural) self-management and not on active human intervention and management. Thus the monitoring program should be continued for such period of time as required by the appropriate authority so as to enable demonstration of a successful transfer from active to passive management (Clause 6(4)(c)).

220. The transition from operational to post-operational phases, from active external management to passive self-management is also reflected in the focus of the monitoring program. While there is overlap there are three phases of monitoring that are discernible, namely:

- during the active stages of decommissioning, stabilisation and rehabilitation of the site, when adherence to the approved design parameters of the decommissioning and rehabilitation program is scrutinised and assessed;

- monitoring which occurs after active rehabilitation measures are completed and prior to the termination of the owner, operator and manager's responsibility for the site with a view to assessing the effectiveness of the rehabilitation as the active management measures are scaled down; and

- if necessary, monitoring carried out (by the appropriate authority or its agents) following termination of the owner, operator, manager's responsibility so as to continue assessment of the impact of the rehabilitated site.

221. Monitoring and inspection in the short term should facilitate early identification of any deficiencies or unforeseen circumstances affecting the decommissioned or rehabilitated site, and hence the choice of appropriate remedial maintenance. In addition the monitoring program should provide information on which an assessment could be made of the behaviour of the rehabilitated site in the long term. Accordingly the monitoring (and inspection) program shall be designed to provide sufficient information to:

- establish which are the critical groups and demonstrate compliance with the basic radiation protection standards contained in the <u>Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (1980)</u>;

- enable the owner, operator and manager to indicate that long-term containment measures are satisfactory and that the decommissioned and rehabilitated site meets the radiological and non-radiological performance objectives for the long-term disposal of wastes as detailed in the approved final rehabilitation plan;

- permit the estimation of future radiological risks associated with the decommissioned and rehabilitated site; and

- allow an assessment of the level of surveillance, maintenance and monitoring required following termination of the owner, operator and manager's responsibility.

222. The Guideline to the <u>Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (1980)</u> entitled: <u>Radiation Monitoring Programs</u>, provides general assistance to those involved in the design and assessment of monitoring programs for approval. Particular monitoring requirements relating to tailings impoundments, waste rock dumps and heap leach piles are discussed in the Guidelines: <u>Tailings Impoundment for Uranium Mines</u>; <u>Waste Rock and Ore Stockpile Management</u>; and <u>Management of Heap Leach Piles</u>.

223. Items of potential impact to be addressed specifically in the development of the monitoring and inspection program include:

- seepage control - acid drainage, groundwater movement;

- erosion and sedimentation management - surface run-off and impact on rehabilitated structures;

- water quality - changes to quality and quantity of receiving surface waters contiguous with the project area;

- gaseous emissions and airborne particulates - radon and radon daughters, airborne radioactive dust;

- stability and visual impact of rehabilitated site - contour and topographical requirements and constraints; and

- maintenance of a vegetative cover.

224. As stated earlier, the monitoring (and inspection) program takes into account the change in requirements of the appropriate authority for the project area. Up to the time of termination of responsibility the owner, operator and manager are responsible for development and implementation of an approved monitoring program. The appropriate authority, as necessary, institutes a system of check monitoring to confirm the validity of the company monitoring program. Following

termination of the owner, operator and manager's responsibility the appropriate authority or its agents have primary responsibility for monitoring and inspection. (This transfer of responsibility, however, does not preclude the establishment of a long-term site surveillance fund by the owner, operator and manager prior to relinquishment of control for the rehabilitated site.)

225. The approach to monitoring outlined above can also be applied to the situation where a project area (or parts of that area) is progressively decommissioned and rehabilitated. Where it is feasible to remove a particular sector from the project area (and the Restricted Release Zone in particular) it would generally be beneficial to do so. The opportunity would thereby be provided to gain experience in rehabilitation of the project area and assess the impacts of various approaches and methodologies. In addition there is an advantage in reducing the area to be rehabilitated at the end of the project.

226. Approval of an amended decommissioning and rehabilitation program would be required whenever the operation underwent significant change, such as temporary suspension. In this circumstance, the decommissioning and rehabilitation program would place the project into a "care and maintenance" mode. The monitoring program for such a project area would anticipate greater reliance on some degree of active inspection and occasional maintenance to the site impoundments and other waste management structures than would occur if the project area was undergoing final decommissioning and rehabilitation.

<u>Maintenance and Surveillance</u>

227. The results of the monitoring and inspections shall be submitted to the appropriate authority on an annual basis or as required by the appropriate authority. Further action and measures as are required by the appropriate authority would be undertaken if such inspections and monitoring reveal the condition of the site to be, or likely to become, unacceptable to the appropriate authority. In effect, for rehabilitation to be successful, it is essential that an adequate maintenance program be developed with the expectation of its implementation in the period during rehabilitation and up to the time of termination of the owner, operator and manager's responsibility for the project area. Thereafter the extent of maintenance should be minimal.

228. This program should include:

- periodic inspections of erosion control works to assess damage caused by scour, sediment deposition, channel obstruction, excessive traffic, loss of vegetative cover or loss of freeboard, and appropriate repairs carried out;

- occasional mowing, where necessary, to control rank growth and to maintain healthy ground cover in channels;

- continual monitoring of vegetative progress which will allow the maintenance program to correct any deficiencies in the protective ground cover;

- demonstration that the decommissioned and rehabilitated site meets the radiological and non-radiological performance objectives for the long-term disposal of the wastes as outlined in the approved final rehabilitation plan;

- assessment of the level of surveillance, maintenance and monitoring required following termination of the owner, operator and manager's responsibility;

- establishment of a fire management policy;

- regular inspection and maintenance of the tailings impoundment and surrounding area by:

  - water sampling and testing of groundwater movement under and surrounding the tailings impoundment;

  - water sampling and testing of surface water below the tailings impoundment and leaving the site;

  - regular seepage surveys;

- inspection and repair of erosion gullies on the retaining embankments; and

- measurements as required of external radiation levels, airborne radioactive contaminants, and radon emanating from the surface of the rehabilitated site.

- formulation prior to final rehabilitation of a policy outlining the preferred land use of the rehabilitated site. The method of rehabilitation could depend on the final land use required of the site.

229. The nature of the maintenance program as outlined above would require discussions between the project management and the appropriate authority. For example, in development of fire management, vegetative regeneration and erosion control works for the project area, the owner, operator and manager would need to be aware of and reorganise the appropriate authority's regional policy for these matters.

<u>Equipment, Techniques and Reporting</u>

230. Clauses 6(4) (d, e and f) of the Code require that appropriate staff, equipment and facilities are available to operate the monitoring program; and that such measurements, examinations and assessments as are required are carried out,

recorded and made available to the appropriate authority. When submitting a monitoring program to the appropriate authority for approval the following details should be given:

- qualifications of the staff to be employed;

- relevant specification and performance of equipment together with calibration sources and methods; and

- description or identification of techniques to be used.

Long Term Site Management

231. As set down in the Code at Clause 16(1) after termination of the owner's, operator's or manager's responsibility such inspection, monitoring and maintenance as may be necessary shall be carried out by the appropriate authority. While it is expected, bearing in mind the aims of a rehabilitation program, that such inspection, monitoring and maintenance would be minimal, it nevertheless will be incumbent on the appropriate authority to undertake these functions when and as required.

232. As noted in paragraph 224 the owner/operator/manager should provide the appropriate authority with an assessment of the level of surveillance, monitoring and maintenance required following termination of their responsibility. On the basis of this assessment the appropriate authority would be able to determine the minimum frequency of site inspections, monitoring requirements and possible maintenance. This assessment will also assist determination of the owner/operator/manager's monetary contribution to the funding of this activity as referred to in paragraph 45 and 46.

233. Surveillance inspections may include direct observation of the physical condition of the site and the sampling of air and groundwater. The inspection team would look particularly for signs of erosion, localised subsidence, seepage, changes in patterns of vegetation, evidence of flooding or flood damage, changes in on-site or nearby streams, measurement and recording of vertical or lateral displacement of bench marks installed during rehabilitation, etc.

234. A program may also be developed for atmospheric sampling on and/or off the site, and for groundwater. Basic plans for groundwater sampling should be made before decommissioning so that any existing sampling wells which are to be retained can be identified and protected during rehabilitation.

235. Maintenance should be performed in accordance with the needs identified in the inspection and monitoring program. However, as noted previously, if a properly designed rehabilitation program has been implemented the maintenance required should be minimal, consisting of minor repairs of surface phenomena. More extensive maintenance may be required in unusual circumstances such as major flooding.

236. **Future Land Use.** Sites where radioactive wastes have been deposited should entail a minimum of restrictions on future land usage but this general aim must be balanced against the consequential effects of meeting public health requirements. The point of balance will depend upon the land use potential of the site, determined by its character, location and type of ownership (i.e. whether it is Crown land, privately owned, a pastoral lease, etc.). These matters would be taken into account by the appropriate authority in determining any restrictions upon land use of the rehabilitated waste disposal sites as required by the Code at Clause 16(2). The appropriate authority may determine that future land use restrictions for a site would preclude the site, or part of the site, from being used for any purpose. In such a case the land might be transferred to the Crown.

237. Specific disposal sites for radioactive waste, such as the tailings impoundment, should be identified as a warning against future disturbance or misuse. Such identification should be in the form of prominent long-lasting markers (such as massive concrete, stone or metal) into which relevant information has been engraved or cast.

238. The most permanent method of identification however, appears to be the endorsement of the appropriate information on local and national land survey plans and title deeds, and the placing of covenants on the use of the land. Thus any obligations would 'run with the land', with the result that upon a change in the ownership of the land, the new owner would incur the obligations. By way of example, the site of the Mary Kathleen operation is to revert to a pastoral lease after rehabilitation, but with special conditions placed on use of the tailings impoundment area.

REHABILITATION PROPOSAL

239. The Code requires decommissioning and rehabilitation proposals to be submitted to the appropriate authority at various stages in the life of a uranium mining and milling operation. The first proposal would be included in the overall waste management program required to be developed before any uranium mining/milling operation commenced (Clause 5(2)). The development of this program is discussed in the Guideline: Development of a Waste Management Program for a Uranium Mining/Milling Operation. This proposal should be periodically reviewed and updated throughout the life of the operation and approved as required by the appropriate authority (Clause 5(3)). Before the permanent cessation of operations a final decommissioning and rehabilitation proposal should be submitted to the appropriate authority for approval (Clause 5(7)).

240. It is apparent that the initial waste management program cannot define in detail the decommissioning and rehabilitation proposals for a particular operation. However, the program should outline the strategy for decommissioning and rehabilitation with particular emphasis on the area of the Restricted Release Zone. This strategy would then be refined throughout the life of the operation, in the light of operating experience and from consultations with the appropriate authority concerning possible changes in land use proposals for the particular area.

241. The final rehabilitation proposal should address all aspects of the project. At most sites the tailings impoundment and the waste rock dumps will present the most difficulties in terms of rehabilitation. Consequently a program of monitoring and testing of the tailings and waste rock should be undertaken thoughout the life of the operation to obtain data required for the final design of the rehabilitation measures.

242. In order to facilitate the final decommissioning and rehabilitation of a site, a committee consisting of technical experts should be established comprising representatives from the mining company, the appropriate authority and their respective technical consultants. The committee should consider the final decommissioning and rehabilitation proposal, the progress of rehabilitation and make recommendations, as appropriate, to the mining company and the appropriate authority.

Final Rehabilitation Proposal

243. The final decommissioning and rehabilitation proposal for the project site should include schedules and plans for the progressive rehabilitation of the mine, mill and waste disposal sites at the termination of mining and milling activities. The proposal should cover in detail the following items:

- plant and equipment;
- mine workings;

- water management system;
- tailings impoundment;
- waste rock;
- ore stockpile areas;
- heap leach piles;
- project site in general (including borrow areas and mine haul roads);
- revegetation; and
- other areas mentioned in paragraph 25.

These items are discussed in detail below.

244. **Plant and Equipment** - The final proposal should include:

- the procedures for the decontamination of plant, equipment and buildings which are proposed to be removed from the site;

- the procedures for disposal of plant and equipment (including buildings) not proposed to be removed from the site; and

- the disposal of contaminated ground, floors and building foundations.

245. **Mine Workings** - The final proposal should include:

- for underground mines:

  - the procedures (including material to be used) to seal all entry points to the mine to prevent the escape of radon and prevent unauthorised entry; and

  - where necessary the installation of suitable drainage provisions to release excess water from the mine. (These drainage points should be made through a seal so that release of radon and unauthorised access to the mine interior is impossible);

- for open cut mines:

  - if the open cut is to be left unfilled the proposal should indicate that it will remain chemically stable and suitable for stock watering or recreational purposes; and

  - if the open cut is to be filled in or used as a waste disposal site then the proposal should detail the requirements for tailings impoundments given in paragraph 243.

246. **Water Management System** - The rehabilitation plan for the water management system should incorporate:

- a design water balance objective line commencing with the volume within the system at the beginning of decommissioning until the end of decommissioning;

- diagrams and plans illustrating the stages of decommissioning of each of the catchment areas within the system and how these catchment areas are removed; firstly from the Restricted Release Zone and secondly from the sediment control zone at which stage they may be considered completely rehabilitated;

- a projected statement of water balance during rehabilitation, taking into account:

  - the design climate for the rehabilitation period;

  - a statement of the total catchment area, total pond area and total water in the system throughout the decommissioning period;

  - a statement of the effects of variations in climate from the design on the period over which decommissioning will take place;

- details of how access will be provided to the site during the rehabilitation, where power supply will come from and how these enter into the overall construction program; and

- an indication of the method of clean-up of the floor of the retention ponds, evaporation ponds and seepage collector ponds and the location of the ultimate disposal of contaminated soils.

247. **Tailings Impoundment** - The final proposal should include but not necessarily be limited to:

- a time schedule for all intended work up to the termination of the owner's, operator's and manager's responsibility;

- properties and quantities of materials to be used for the rehabilitation structures;

- locations from where such materials will be obtained;

- details of zoning of the cover structures and reasons for each zone;

- expected settlement of the tailings;

- proposed drainage profile for the surface of the cover structures and how allowance will be made for expected settlements;

- methods and structures proposed for discharge of rain runoff water;

- expected location of the phreatic surface in the impoundment and seepage flows from the impoundment prior to rehabilitation work, during the transitional period and over the long-term;

- an assessment of the range of the rates of radon exhalation and gamma ray emission over the surface of the rehabilitated tailings impoundment for the expected range of moisture contents in tailings and various zones of the cover structure;

- expected long-term life of the cover structure and basis for such a prediction; and

- monitoring and inspection program to be carried out by the owner/operator/manager on the behaviour of the tailings, seepages from the impoundment, pore water pressures in the tailings, rainwater infiltration, moisture content and water quality in various zones of the rehabilitation of structures, measurements of radon exhalation and gamma ray emission, rainwater runoff, quality and quantity, settlements of rehabilitated surfaces, vegetation growth and fauna re-establishment. This program should include provision for assessment (quantitative and qualitative) of the progress of the rehabilitation program.

248. **Waste Rock** - For waste rock the final proposal should include but not necessarily be limited to:

- final shape of the waste rock dump;

- layout of surface drainage systems and determination of flow quantities and velocities at various locations for a range of rainfall events;

- details of drainage structures;

- details of surface water monitoring stations and groundwater observation bores; and

- methods of measuring contamination levels in surface water and groundwater and prediction of yearly contaminant levels to be achieved until the final hand over.

249. **Ore Stockpile Areas** - For ore stockpile areas the final proposal should include:

- methods to be used to determine the amount of specified material remaining in the stockpile bases, the degree to which the bases should be decontaminated and the methods to be used for disposal of contaminated surface material;

- details of surface preparation for stabilisation and revegetation;

- details of surface drainage design;

- methods to be used to determine contamination in groundwater and runoff water, predictions of possible groundwater and runoff water contamination and comparison with long term water quality goals.

250. **Heap Leach Piles** - If heap leaching is employed at the site the proposal should detail the proposed method of disposal of the heap leached material, the neutralisation procedures to be used and the contaminant potential of the material. The information required concerning the rehabilitation of the heap leach base is as described above for ore stockpile areas.

251. **Project Site in General** - With regard to the project site in general the final proposal should include:

- methods for the disposal of contaminated ground, road bases, drains, hardstand areas, etc; and
- the predicted levels of contamination of the project area following rehabilitation.

252. **Revegetation** - The final proposal should be drawn up in consultation with agriculture, soil conservation and water resource authorities and design engineers and should include:

- a description of the procedures for site preparation for revegetation including shaping, topsoiling, ripping and ploughing;
- techniques for establishing plant growth including species, seed and fertiliser rates, seeding techniques, irrigation, mowing;
- expected seral progression of the vegetation until termination of owner/operator/managers responsibility and for subsequent periods until a climax vegetation is obtained;
- surface erosion control works to control overland flows;
- a description of the procedures to be employed to measure growth, regrowth, species and ground cover and expected values for these parameters; and
- a maintenance program, including standards, scheduling, number of personnel, costs and length of program.

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253. The following references provide a broad overview of methods and technologies for the decommissioning and rehabilitation of uranium mines, mills and waste disposal sites. However, it should be noted that new methods and technologies are being continuously developed and introduced.

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FIGURE 1 SOIL ATTENUATION ^{238}U Series

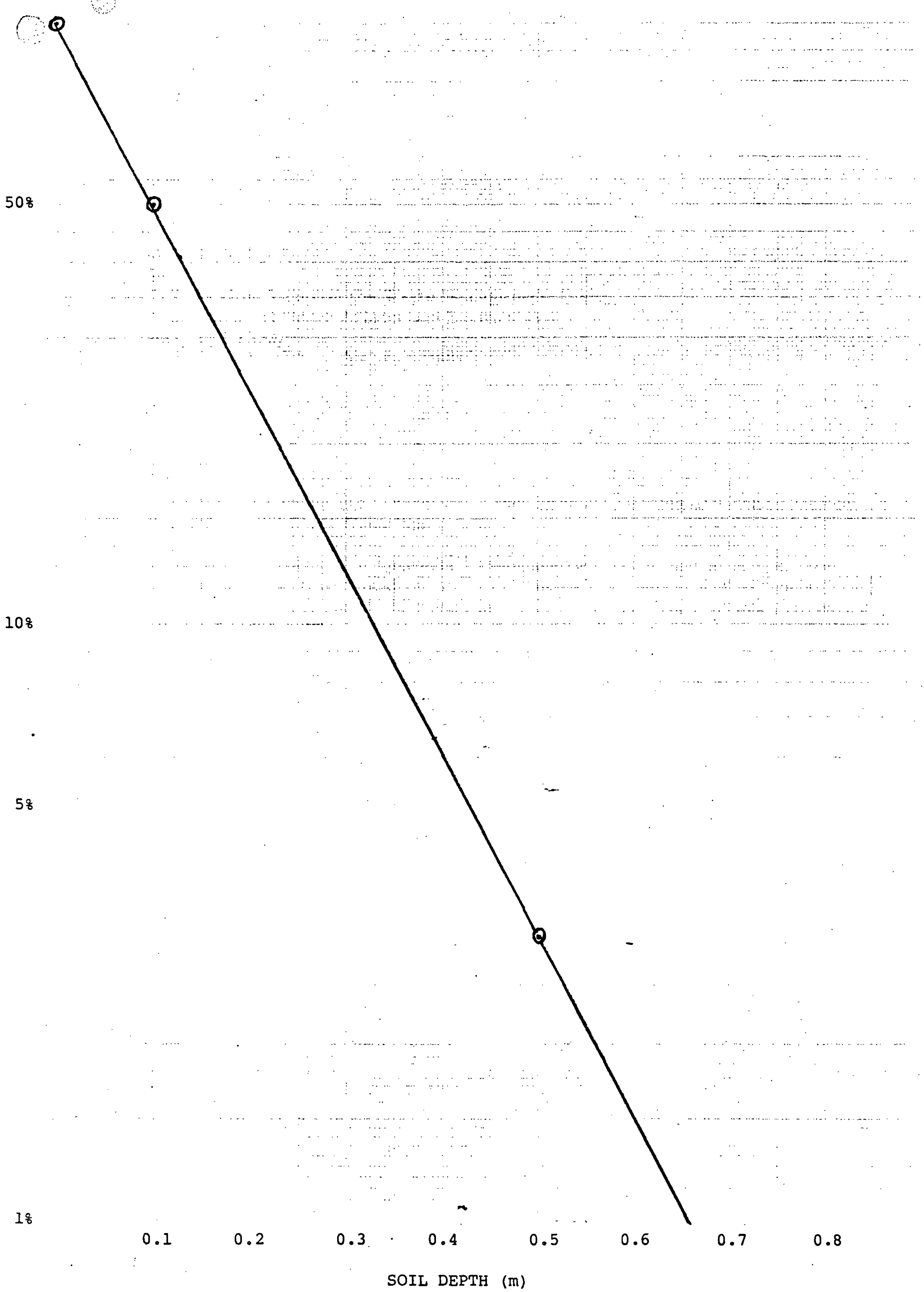
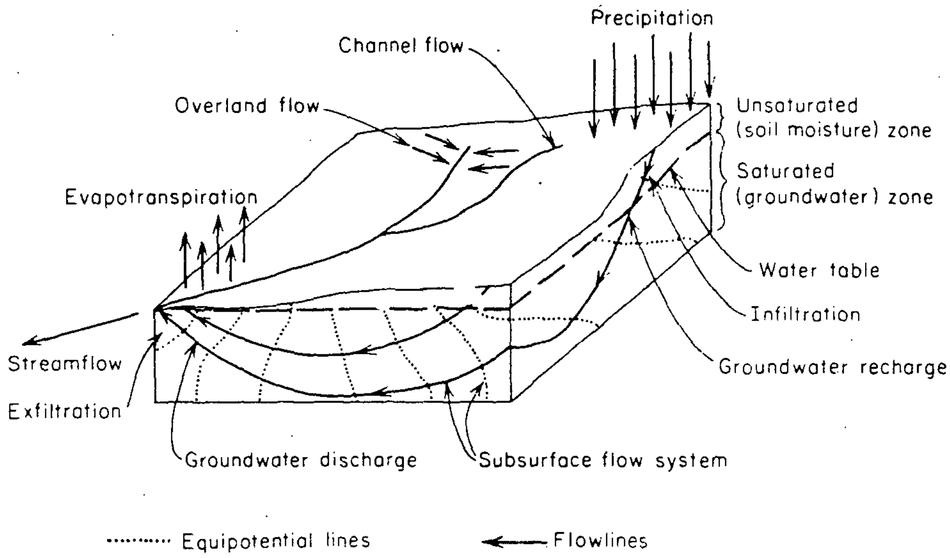
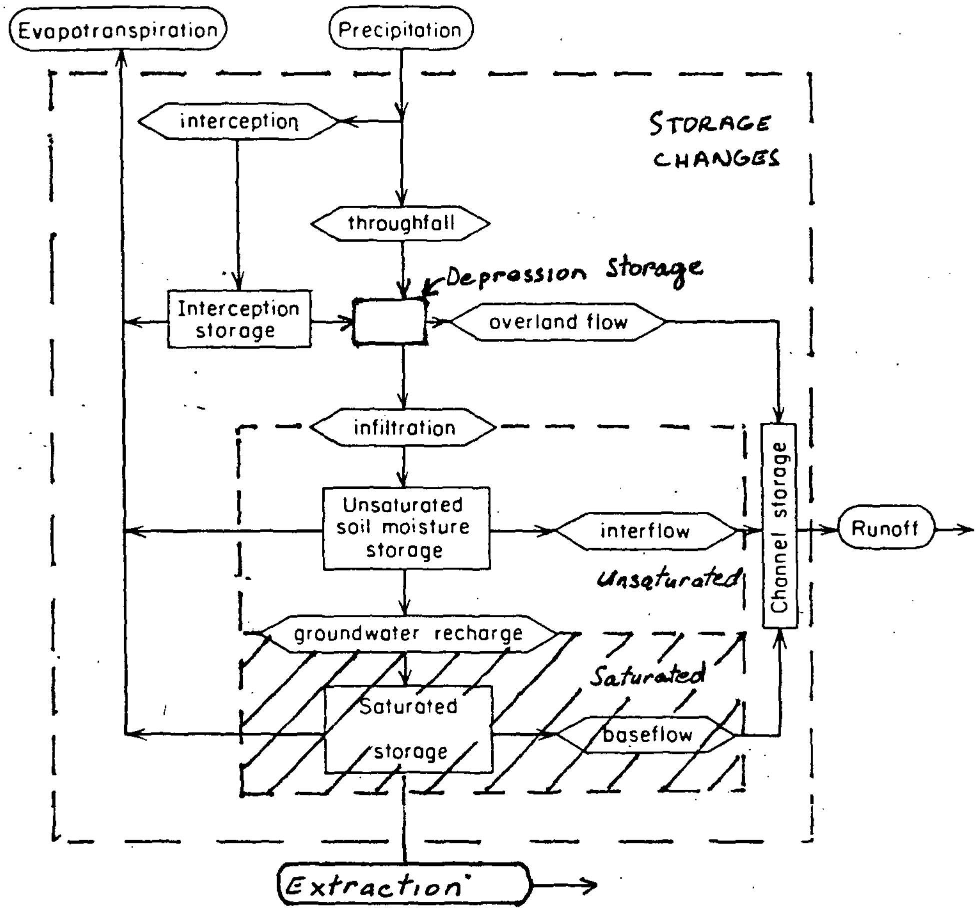


Figure 2 Schematic representation of the hydrologic cycle.





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APPENDIX I

MECHANISM OF RADON EXHALATION AND METHODOLOGY FOR ESTIMATING RADON EXHALATION RATES

Section 1 - Mechanism of Radon Transport through Tailings

Release of radon to the atmosphere involves two mechanisms, liberation from the individual grain in which it is formed and transport through porous media to a free surface. The fraction of radon atoms formed that escape the mineral grain is termed the emanation coefficient. The transport of radon through media is usually characterised by the diffusion coefficient in the bulk medium.

Radon is formed in tailings by decay of radium. The radon atom has a recoil energy of 10^5eV which allows it to travel about 0.03 μm in rock, 0.1 μm in water and 64 μm in air. At the termination of its recoil trajectory it will move further by diffusion. Approximate diffusion coefficients are $10^{-21}cm^2/s$ in rock crystals, $10^{-5}cm^2/s$ in water and $10^{-1}cm^2/s$ in air. From the relative magnitudes of these coefficients it can be shown that diffusion through rock does not contribute greatly to the release of radon. However, if the recoil terminates outside the particle or in an open pore, the radon is able to migrate to a free surface.

The radon emanation coefficient increases with moisture content until a constant value is reached (Strong and Levins 1982, Nielson et al 1982). This behaviour can be attributed to the ability of absorbed water, in the pores, to trap the radon recoil atom. At low moisture contents most of the radon escaping from grains bury themselves in other grains. However, if the pores contain water rather than air the recoiling radon atom encounters a dense absorber of its energy. Radon absorbed in a water film can interchange with the air and diffuse through the air space in the pore. The emanation coefficient becomes constant at a moisture content where the water film is just thick enough to stop all radon recoil atoms.

The diffusion coefficient of radon in air is four orders of magnitude greater than that through water. So, as moisture content in the tailings is increased the diffusion coefficient through the tailings decreases rapidly. At low moisture contents, water is totally absorbed into the tailings and has little effect on the rate of radon diffusion. As moisture content is increased, free moisture content is increased, free moisture begins to appear in the interstitial space. This space progressively fills with water until all pores are full and the diffusion rate is decreased by four orders of magnitude. Figure 1 shows the effect of moisture content on the diffusion coefficient for an Australian tailings pile.

The flux from tailings increases with moisture content up to a maximum, which corresponds to the appearance of interstitial water. As the moisture content is further increased the flux decreases rapidly.

Section 2 - Mechanism of Radon Transport through Waste Rock

While diffusion is considered to be the dominant mechanism for radon transport in tailings, advection is considered to be the dominant transport mechanism in waste rock dumps. This may be due in part to the uncompacted nature of the waste rock material. Advection can result, for example, from temperature gradients within the dump, gas generation within the dump, atmospheric pressure changes outside the dump or the effect of wind velocity on and over the dump. Advective processes will in general transport gas at higher rates than diffusive processes. Measurements in the Rum Jungle waste rock dumps have shown that advective processes, driven by temperature gradients caused by pyritic oxidation within the dumps and atmospheric pressure changes, dominate over diffusive processes in many parts of these dumps. Other mechanisms such as wind effects and surface temperature changes appear to be of little significance.

Gas transport rates will depend on the porosity and permeability of the dumps. The porosity can change as the dump material weathers, chemical reactions within the dump can produce precipitates that reduce the porosity and block channels within the dump while water percolating through will also reduce porosity and block channels. It is evident that the construction technique used for the Rum Jungle waste dumps has resulted in a high permeability region near the base of the dumps which has aided gas transport by convection.

Section 3 - Mathematical Modelling of Radon Transport

The following models allow the estimation of radon flux from uncovered tailings and waste rock dumps, and rehabilitated tailings impoundments and waste rock dumps covered with up to three layers of cover material. The equations are based on gas transport by diffusion processes. While it is noted above that advection processes also operate in waste rock dumps it is considered that the diffusion models can be used to give a close approximation of the radon flux. Nomenclature used in the following equations is described in Figure 2 and Section 4.

The general equation for radon transport through a tailings pile is

$$\frac{\partial C}{\partial t} = D \frac{\partial 2C}{\partial x^2} - \lambda C + \frac{P\rho}{\varepsilon} \qquad (1)$$

The radon production rate (P) is related to the emanation coefficient (E) and the radium content (R) by

$$P = ER\lambda \qquad (2)$$

Where λ is the decay constant for radon ($2.1 \times 10^{-6} s^{-1}$).

The emanation coefficient, E, range is typically between 0.1 and 0.2. The diffusion coefficient, D, is related to the molecular diffusion coefficient (D_m) by the equation

$$D = \gamma D_m \qquad (3)$$

Where γ is the tortuosity factor which is about 0.66 for dry soils. The effective diffusion coefficient (D_e), a term which is often used in the literature, is related to the diffusion coefficient by

$$D_e = D\varepsilon = D_m \gamma \varepsilon \qquad (4)$$

D_e arises when flux is defined in terms of the apparent cross-sectional area rather than the true area. In this appendix only the diffusion coefficient is used.

Equation (1) describes transport of radon through tailings and cover material. However, the radon production rate in the cover material is usually insignificant. The contribution of local cover materials to flux is usually ignored as it is considered to be background exhalation. A system of equations describing radon transport through tailings and a number of layers of covering materials may be solved for appropriate boundary conditions. The most appropriate boundary conditions being:

- radon flux at the base of the tailings is zero;
- flux and concentration are continuous across solid interfaces; and
- radon concentration at the solid/air interface is zero.

Solutions to the general transport equation using these boundary conditions are as follows

Bare Tailings

The radon surface flux is given by

$$J_{\text{bare tailings}} = P_t \rho_t \frac{D_t}{\lambda} \tanh \alpha_t H_t \qquad (5)$$

For most practical applications where the tailings are thicker than 3m tanh αh approaches unity and Equation (5) becomes

$$J \text{ bare tailings} = P_t \rho_t \frac{D_t}{\lambda}$$

Covered Tailings

Equations (6), (7) and (8) give the theoretical surface flux from tailings covered with 1, 2, and 3 layers of covering materials containing insignificant radium, respectively.

One layer

$$J_1 = \frac{P_t \rho_t \dfrac{D_t}{\lambda} \dfrac{\tanh \alpha_t H_t}{\cosh \alpha_1 H_1}}{\left(1 + \dfrac{\varepsilon_t}{\varepsilon_1} \dfrac{D_t}{D_1} \tanh \alpha_t H_t \tanh \alpha_1 H_1\right)} \tag{6}$$

Two layers

$$J_2 = \frac{P_t \rho_t \dfrac{D_t}{\lambda} \dfrac{\tanh \alpha_t H_t}{\cosh \alpha_2 H_2 \cosh \alpha_1 H_1}}{\left(1 + \varepsilon_t D_t \tanh\alpha_t H_t \left(\dfrac{\tanh\alpha_1 H_1}{\varepsilon_1 \quad D_1} + \dfrac{\tanh\alpha_2 H_2}{\varepsilon_2 \quad D_2}\right) + \dfrac{\varepsilon_1}{\varepsilon_2} \dfrac{D_1}{D_2} \tanh\alpha_1 H_1 \tanh\alpha_2 H_2\right)} \tag{7}$$

Three layers

$$J_3 = \frac{P_t \rho_t \dfrac{D_t}{\lambda} \dfrac{\tanh\alpha_t H_t}{\cosh\alpha_3 H_3 \cosh\alpha_2 H_2 \cosh\alpha_1 H_1}}{K}$$

$$\text{where } K = \left(1 + \varepsilon_t \quad D_t \tanh \alpha_t H_t \left(\frac{\tanh\alpha_1 H_1}{\varepsilon_1 \quad D_1} + \frac{\tanh\alpha_2 H_2}{\varepsilon_2 \quad D_2} + \frac{\tanh\alpha_3 H_3}{\varepsilon_3 \quad D_3}\right)\right. \tag{8}$$

$$+ \frac{\varepsilon_1}{\varepsilon_2} \frac{D_1}{D_2} \tanh\alpha_1 H_1 \tanh\alpha_2 H_2 + \frac{\varepsilon_2}{\varepsilon_3} \frac{D_2}{D_3} \tanh\alpha_2 H_2 \tanh\alpha_3 H_3$$

$$+ \frac{\varepsilon_1}{\varepsilon_3} \frac{D_1}{D_3} \tanh\alpha_1 H_1 \tanh\alpha_3 H_3$$

$$\left. + \frac{\varepsilon_t \varepsilon_2}{\varepsilon_1 \varepsilon_3} \frac{D_t D_2}{D_1 D_3} \tanh\alpha_t H_t \tanh\alpha_1 H_1 \tanh\alpha_2 H_2 \tanh\alpha_3 H_3\right)$$

The case of tailings covered with a single layer containing radium is given in Hart et al (1984).
A flux attenuation factor can be defined as a measure of the effectiveness of one or more layers of covering material

$$F_n = \frac{J_{\text{bare tailings}}}{J_n} = \frac{\text{Flux from bare tailings}}{\text{Flux from covered tailings (n layers)}} \tag{9}$$

Equations (10), (11) and (12) give the flux attenuation factors applicable for 1, 2 and 3 layers of covering material, respectively.

One layer

$$F_1 = \cosh\alpha_1 H_1 \left(1 + \frac{\varepsilon_t}{\varepsilon_1} \frac{D_t}{D_1} \tanh\alpha_t H_t \tanh\alpha_1 H_1\right) \qquad (10)$$

Two layers

$$F_2 = \cosh\alpha_2 H_2 \cosh\alpha_1 H_1 \left(1 + \varepsilon_t D_t \tanh\alpha_t H_t \left(\frac{\tanh\alpha_1 H_1}{\varepsilon_1 D_1} + \frac{\tanh\alpha_2 H_2}{\varepsilon_2 D_2}\right)\right.$$

$$\left.\frac{\varepsilon_1}{\varepsilon_2} \frac{D_1}{D_2} \tanh\alpha_1 H_1 \tanh\alpha_2 H_2\right) \qquad (11)$$

Three layers

$$F_3 = K\cosh\alpha_1 H_1 \cosh\alpha_2 H_2 \cosh\alpha_3 H_3 \qquad (12)$$

where K is defined as for Equation (8).

Flux attenuation factor for tailings covered by any number of different layers which do not contain radium may be calculated (Hart et al 1984).

Equations (10), (11) and (12) can be used in conjunction with Equation (5) to predict the radon flux from any rehabilitation scheme involving up to three different layers. The physical parameters that must be known are, for the tailings:

- the radium content,
- emanation coefficient,
- voidage, and
- diffusion coefficient,

and for each covering layer

- voidage, and
- diffusion coefficient.

Example

Using the foregoing equations and discussion it is possible to estimate the effectiveness of a rehabilitation scheme. Consider a tailings dam which is to be rehabilitated using the scheme shown in Figure 3.

Bare tailings

uranium head grade	0.2 per cent U
calculated radium concentration	25 Bq g^{-1}
emanation coefficient	0.2
bulk density	1100 kg m^{-3}
voidage	0.6
diffusion coefficient	1.6 x 10-7 m^2 S^{-1} (from figure 1 for 12 wt per cent moisture)
depth of tailings	10 m
radon production rate	1.05×10^{-2} Bq $kg^{-1}s^{-1}$ (calculated from equation (2))

From Equation (5) the flux from bare tailings is given by

$$J_{bare\ tailings} = 1.05 \times 10^{-2} \times 1100 \frac{1.6 \times 10^{-7}}{2.1 \times 10^{-6}} \times 1$$

$$J_{bare\ tailings} = 3.19 \text{ Bq } m^{-2}s^{-1}$$

Covered tailings	Cover 1 clay	Cover 2 gravel	Cover 3 soil
voidage	0.3	0.4	0.33
moisture content (wt per cent)	12	dry	5
diffusion coefficient (m^2s^{-1}(from Figure 2))	2×10^{-7}	7.9×10^{-6}	3×10^{-6}
depth of layer (m)	0.45	0.2	1.0

The flux attenuation factor may be calculated from Equation (12)

$\tanh \alpha_t H_t = 1$ $\cosh \alpha_1 H_1 = 2.27$ $\epsilon_t \; D_t = 2.4 \times 10^{-4}$

$\tanh\alpha_1 H_1 = 0.90$ $\cosh\alpha_2 H_2 = 1.01$ $\varepsilon_1 \; D_1 = 1.3 \times 10^{-4}$

$\tanh\alpha_2 H_2 = 0.10$ $\cosh\alpha_3 H_3 = 1.37$ $\varepsilon_2 \; D_2 = 1.1 \times 10^{-3}$

$\tanh\alpha_3 H_3 = 0.68$ $\varepsilon_3 \; D_3 = 5.7 \times 10^{-4}$

$$F = 2.27 \times 1.01 \times 1.37 \times (1 + 2.4 \times 10^{-4}(6923 + 90.9 + 1193.0) + 0.01 + 0.13 + 0.14 + 0.22)$$

$F = 10.89$

Flux from rehabilitated tailings = 0.39 Bq m^{-2} s^{-1}

Section 4 - Description of the Nomenclature Used in the Equations, and Determination of the Respective Parameters Required

Main Terms

C	interstitial concentration of radon (Bq m^{-3})
D	diffusion coefficient (m^2 s^{-1})
D_e	effective diffusion coefficient (m^2 s^{-1})
D_m	molecular diffusion coefficient (m^2 s^{-1})
E	emanation coefficient
F	flux attenuation factor
H	layer thickness (m)
J	surface flux (Bq m^{-2} s^{-1})
P	radon production rate (Bq kg^{-1} s^{-1})
R	radium content (Bq kg^{-1})
t	time (s)
x	distance from the base of the tailings (m)

Greek Letters

α	inverse of the diffusion length: $\frac{\lambda}{D}$ (m^{-1})
γ	tortuosity
ε	porosity (voidage) in tailings or covering layer
λ	decay constant for radon (2.1×10^{-6} s^{-1})
ρ	bulk density (kg m^{-3})

Subscripts

t refers to tailings

1,2,3 refer to covering layer 1, 2 and 3 respectively.

Radon Emanation Coefficient

The radon emanation coefficient is defined as that fraction of radon formed which escapes the mineral grain. Methods for determining the emanation coefficient are based on the measurement of the build-up of radon activity in sealed samples. Commonly, measurements are made either by direct gamma assays of the container or by collection and alpha counting of the released radon gas.

The simplest and perhaps the most widely used technique is to measure the difference between two gamma assays of a sealed sample (Austin and Droullard 1978). The radon activity is determined indirectly using the 0.609 MeV gamma ray of its daughter bismuth-214. The first gamma count is carried out as soon as the sample is sealed, when the contribution of gaseous radon is close to zero. The sample is then counted after thirty days have been allowed for radon to reach secular equilibrium with its precursor radium-226. The emanation coefficient is calculated as the difference in countrates divided by the countrate at equilibrium. This method has the advantages of using simple counting equipment and being nearly independent of equipment calibrations and related counting biases. It becomes imprecise for very low emanation coefficients due to small differences between the two gamma assays.

The second method which is particularly sensitive for low emanation coefficients involves the direct measurement of radon released from the sample (Strong and Levins 1982). The sample is initially purged of any radon in the air space and then sealed for at least four days to allow radon to accumulate. A known volume of gas is transferred to an evacuated scintillation cell. The α activity is determined when radon has reached equilibrium with its daughters. The emanation coefficient is calculated as the released radon activity divided by the sample's radium content. The emanation coefficient usually ranges between 0.1 and 0.2.

Diffusion Coefficient

The diffusion coefficient for radon through materials has been measured using a number of methods. Laboratory techniques include estimating diffusion coefficients from measured flux and concentration profiles by comparison with those predicted from diffusion theory (Strong et al 1981, Nielson et al 1981 and Hartley et al 1981). And for covering materials the diffusion coefficient may be estimated by measuring the transport of radon from a source through the covering material (Silker and Rogers 1981 and Hartley et al 1981). Field techniques have also been used to estimate the diffusion coefficient from flux measurements (Schroeder et al 1965) and by gamma logging of boreholes in tailings dams (Silker et al 1979). All of these techniques require different complexities of equipment and laboratory facilities. Care should be taken to use the most accurate technique commensurate with the available resources. Table 1 gives the diffusion coefficient for radon in various media.

Section 5 - Measurement of Radon Flux

The measurement of radon flux from bare and rehabilitated tailings piles is complicated by temporal and spatial variations in flux which will be encountered at any given site.

Spatial Variations

The flux from a tailings pile varies with actual location on the pile because of variations in the following;

- Thickness of the pile;
- Particle size of the tailings (distribution of the sand and slimes fraction within the pile);
- Radium-226 concentration (also related to distribution of sands and slimes fraction)
- Moisture content;
- Emanating power of the tailings and cover material.

The variations of the radon flux across the covered rehabilitated tailings disposal site would be expected to be less than across a bare tailings disposal site. However, if cover material was not uniform or if cracks develop in it, the spatial variation of the radon flux from a covered tailings pile could be greater.

Legett et al (1978) have described a method for calculating the number of locations at which a parameter must be measured to determine its average value with a precision of 25 per cent at a 95 per cent confidence level.

Number of locations = 45 (Coefficient of Variation)^2.

Coefficients of Variation of radon flux measurements obtained from tailings piles in the USA range from 0.66 for tailings covered by 15cm of soil to 0.84 for bare tailings (Ford, Bacon and Davis Inc, 1981). This would mean that between 20 and 32 measurements would be required to obtain an average radon flux value if the empirical relationship of Legett et al was used.

Temporal Variations

The radon flux from a given location at the disposal site will also show considerable variation with time as a result of changes in meteorological conditions, moisture content of the tailings and cover material and perhaps settling of the cover material.

The meteorological factors influencing the radon flux are in order of decreasing importance, according to Baver (1956):

. Rainfall;
. Variations in barometric pressure;
. Variations of soil and atmospheric temperature;
. Wind speed.

The radon flux may be expected to show systematic diurnal variations as well as seasonal variations because of the abovementioned meteorological factors. To allow for diurnal variations, radon flux measurements should, if possible, be made over time periods that are multiples of 24 hours. The seasonal variations should also be allowed for by ensuring that radon flux measurements are measured at uniform intervals throughout the year so that a more realistic value for the average radon flux can be estimated.

Young et al, (1983) examine in detail all the above aspects on flux variations and methods of determining the number of sampling sites and frequency of flux measurement to minimise the effects of these variations.

Radon Flux Measurement Techniques

Various methods and instrumentation types are available for measuring radon flux. A description of the main methods along with an account of possible procedures for conducting radon flux surveys are also presented by Young et al, (1983). The methods available include:

- The Charcoal Canister Methods;
- The Flow Method;
- The Accumulation Method;
- Track-Etch and Thermoluminescent Dosimeter (TLD) Detector Method.

Each of these procedures have advantages and drawbacks. Overall, the charcoal canister method appears to be the most effective method in terms of cost and effort for measuring the average radon flux across a large area such as a rehabilitated tailings disposal site or waste rock sites. The Track-Etch and TLD detectors measure radon concentration rather than the radon flux. Simultaneous measurements of concentration and flux would need to be made to derive empirical factors relating concentrations to fluxes for site specific meteorological conditions and material types.

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TABLE 1 DIFFUSION COEFFICIENTS FOR RADON IN VARIOUS MEDIA[a]

Medium	Moisture Content per cent	Diffusion Coefficient (D) (cm^2/sec)
Air		1.0 to 1.2E-1
Water	100	1.13E-5
Sand		
Fine quartz	0	6.8E-2
Building sand ($1.40 g/cm^3$, 39 per cent voids)	4	5.4E-2
Fine quartz	8.1	5.0E-2
Fine quartz	15.2	1.0E-2
Fine quartz	17	5.0E-3
Soils		
Granodiorite		4.5E-2
Yucca Flats (25 per cent voids)[b]		3.6E-2
Metamorphic rock		1.8E-2
Granite		1.5E-2
Loams		8.0E-3
Varved clays		7.0E-3
Mud ($1.57 g/cm^3$)	37.2	5.7E-6
Mud ($1.02 g/cm^3$)	85.5	2.2E-6
Concrete, (5 per cent voids)[c]		3.4E-4

[a]Tanner, A.B., (1964) 'Radon migration in the ground', in The Natural Radiation Environment, Adams, J.A.S. and Lowder, W.M. eds., published for Rice University by University of Chicago Press, Chicago, p.166.

[b]Kraner, H.W., Schroeder, G.L. and Evans, R.D. 'Measurements of the effects of atmospheric variables on radon-222 flux and soil-gas concentrations', The Natural Radiation Environment, op, cit., p.210.

[c]Culot, M.V.J., Olson, H.G. and Schrager, K.J. (1973) 'Radon progeny control in buildings', Final Report on EPA Grant ROI EC00153 and AEC Contract AT(11-)-2273, Colorado State University, Fort Collins, Colorado, pp.80, 155.

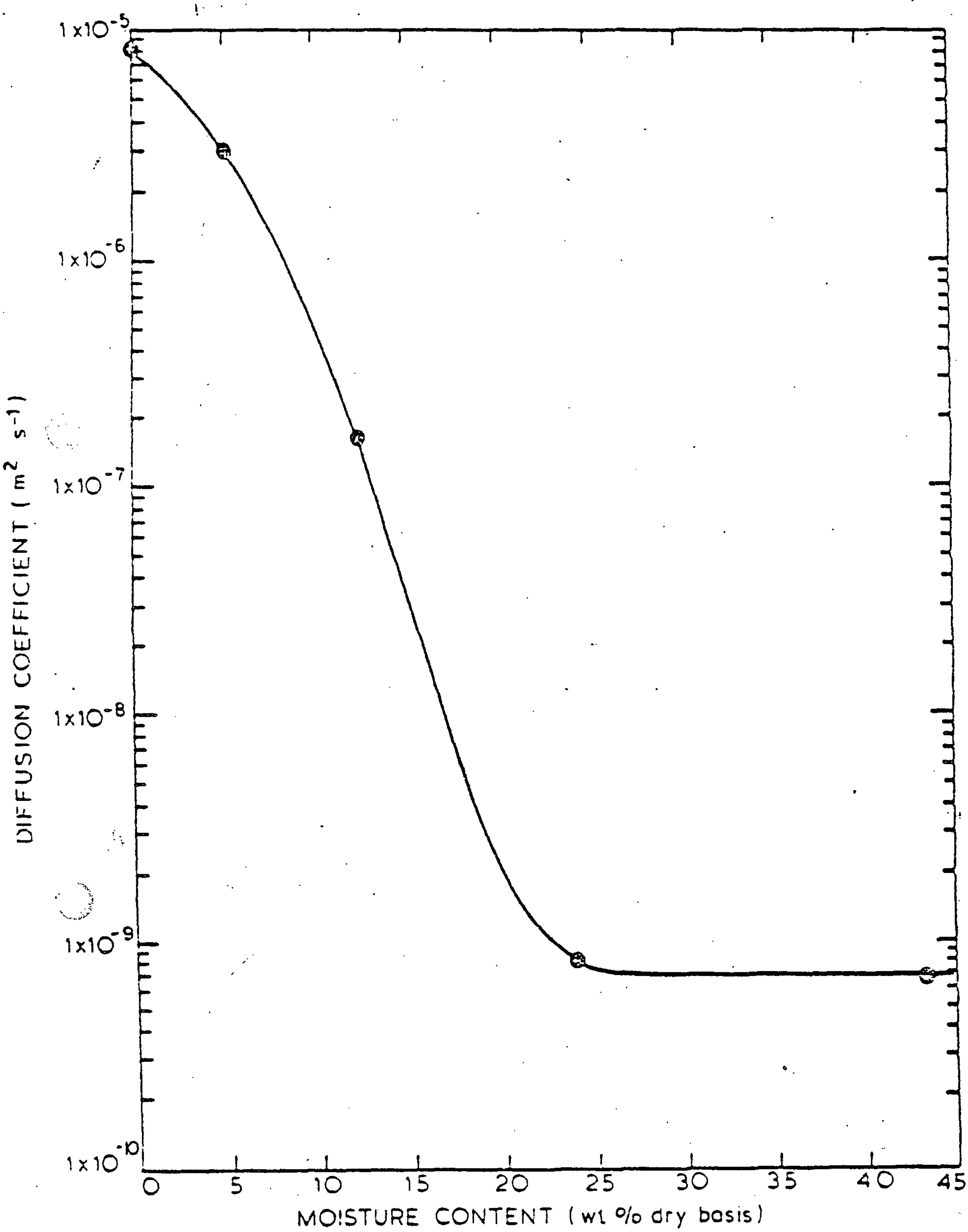

FIGURE 1 EFFECT OF MOISTURE CONTENT ON DIFFUSION COEFFICIENT TYPICAL FOR AUSTRALIAN TAILINGS

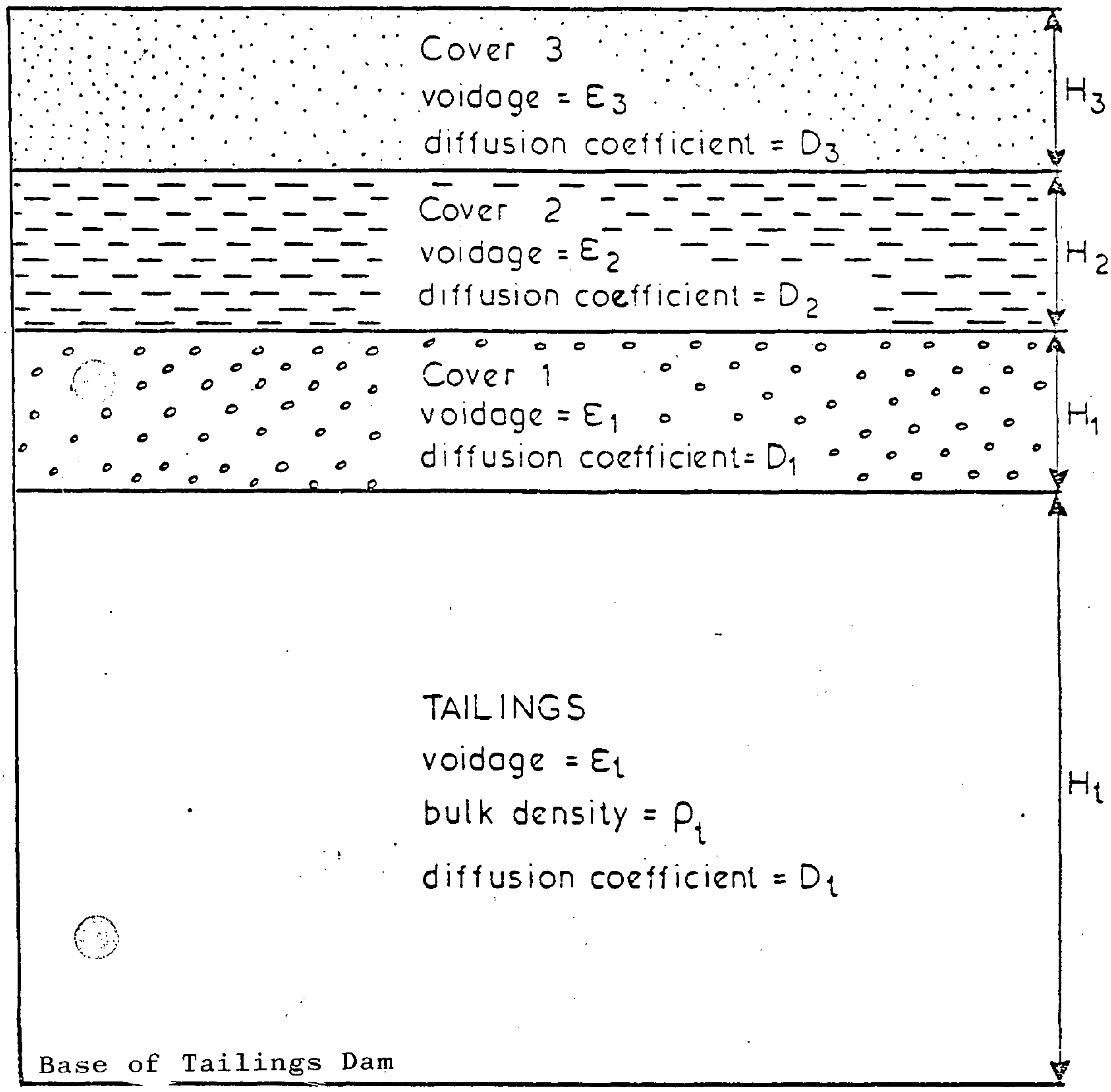

FIGURE 2. NOMENCLATURE FOR COVERED TAILINGS

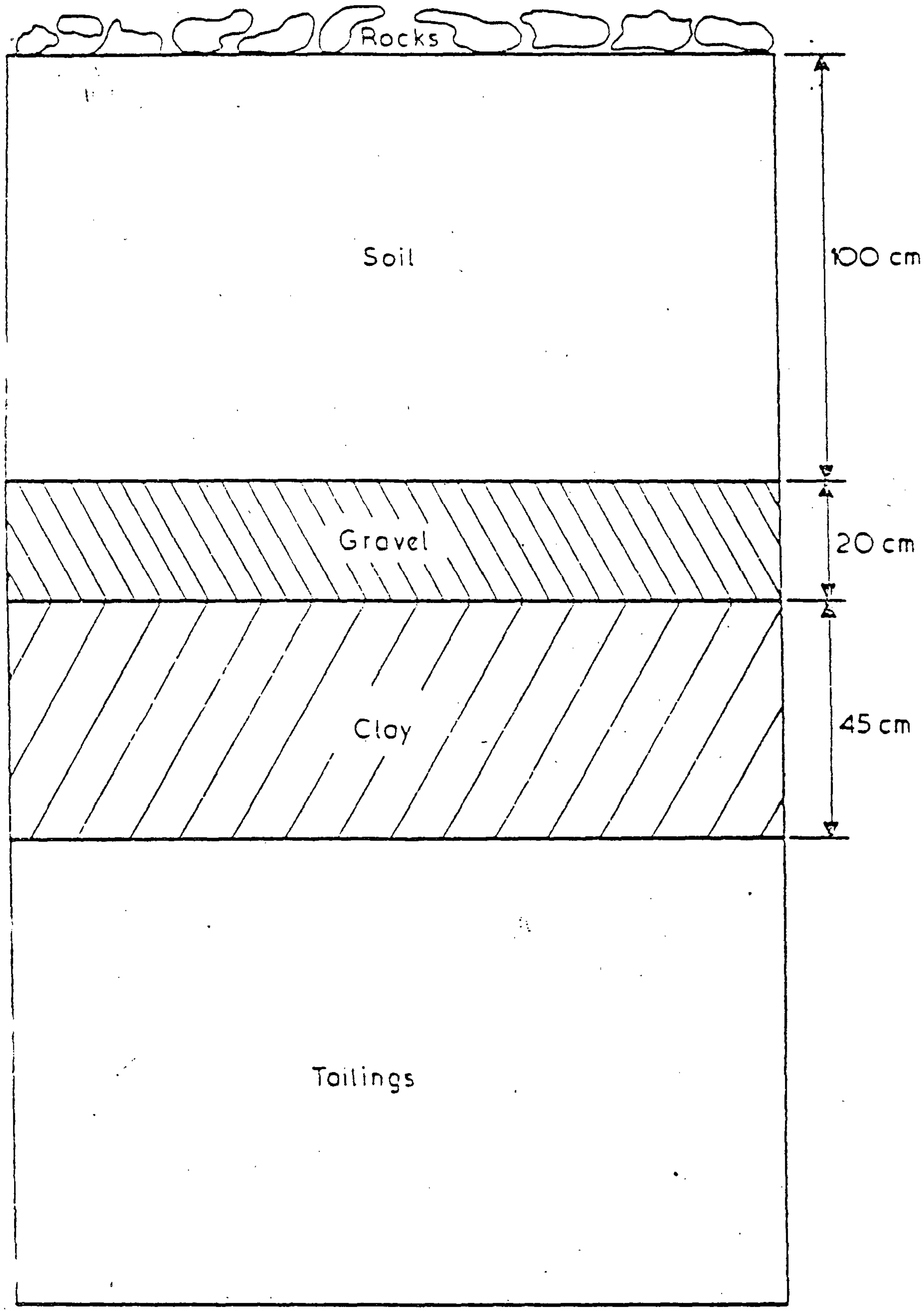

FIGURE 3 AN EXAMPLE OF A HYPOTHETICAL REHABILITATION SCHEME

APPENDIX II

EXAMPLE OF METHOD OF DETERMINING A SOIL CONCENTRATION LIMIT

It is assumed that the decommissioned site will be accessible to members of the public for recreational purposes, including some horticulture and that the nearest residences are 5 km away.

External Dose

Recreational occupancy is assumed to average 2 h per day.

A uniform ground contamination of 1 Bq g^{-1} of U-238 and its daughters would result in a dose rate at 1 m above ground of 1.58 μrad h^{-1} per pCi g^{-1}(Ref.1) or 0.43 μSv h^{-1} per Bq g^{-1}. The annual external dose would thus be 0.43 x 2 x 365 = 314 μSv per Bq g^{-1}.

Internal Dose

a) Ingestion

A typical annual consumption of vegetables is 350 kg. It is assumed that no more than half of anyone's vegetable consumption comes from the rehabilitated site.

It is also assumed that equal amounts of uranium, thorium, lead and polonium are available in the soil, and that the critical group is adult, having the characteristics of reference man.

TABLE 1

Radio-nuclide	Uptake Factor Bq g^{-1} fresh food per Bq g^{-1} dry soil (Ref.2)	Annual Intake Bq	Most Restrictive Ingestion ALI Bq (Ref 3)	Dose Equivalent μSv
U-238	2×10^{-3}	3.5×10^{-4}	5×10^{5}	3.5×10^{-5}
U-234	2×10^{-3}	3.5×10^{-4}	4×10^{5}	4.4×10^{-5}
Th-230	5×10^{-4}	8.75×10^{-5}	1×10^{5}	4.4×10^{-5}
Ra-226	4×10^{-2}	7×10^{-3}	7×10^{4}	5×10^{-3}
Pb-210	1×10^{-2}	1.75×10^{-3}	2×10^{4}	4.4×10^{-1}
				9.5×10^{-3}

b) Inhalation

For infinite thickness uranium mill tailings the exhalation rate of radon 222 per unit activity concentration of radium 226 is assumed to be 1.6 pCi m^{-2} s^{-1} per pCi g^{-1} or
1.6 Bq $m^{-2}s^{-1}$ per Bq g^{-1} (Ref. 1).

Assuming a site area of 100 ha, using a simple gaussian air dispersion model (Pasquill Category F, wind speed of 2 m s^{-1}), then the radon concentration 5 km downwind would be about 1.34 Bq m^{-3}. Assuming a radon equilibrium factor of 0.4, 1.34 Bq m^{-3} corresponds to 0.14 mWL.

Assuming that the wind only blows towards the house at 5 km for 50 per cent of the time, the annual dose per Bq g^{-1} of radium 226 in soil would be approximately 10 μSv.

A correction should be made to this estimated dose to take account of time away from the house, including the two hours assumed to be spent recreationally each day at the rehabilitated site.

Total Exposure

Using the model defined above, the exposure of a member of the critical group would be:

$314 + 9.5 \times 10^{-3} + 10 = 324$
say 300 μSv per Bq g^{-1} of Ra-226 in the soil.

Implied Limit from this Hypothetical Estimate

If the regulatory objective were, for example, to limit critical group exposure to 500 μSv per year, then for this site a soil contamination limit of:

$\frac{500}{300} = 1.7$
say 1.5 Bq g^{-1} of Ra-226 in soil would be appropriate.

The suggested limit of 1.5 Bq g^{-1} of Ra-226 would give rise to a gamma dose rate 1 m above the ground surface of about 54 nSv h^{-1}. In order to detect this dose rate above the natural background level (which will usually be of the order of 100 nSv h^{-1}) with a handheld dose rate instrument, careful selection of a suitable instrument, and good records of natural background levels will be necessary.

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APPENDIX III

EXAMPLE 1

USE OF A WATER BALANCE METHOD TO PREDICT SEEPAGE BEHAVIOUR OF A HYPOTHETICAL REHABILITATED TAILINGS IMPOUNDMENT

In this example a study for determining the seepage behaviour of a cover cap was undertaken using a water balance (or a hydrologic budget) method. This was extended to give an indication of the behaviour of the water table in the tailings, foundation and the dam structures.

The water balance approach requires the collection (or simulation) of considerable data relating to climate, plant growth, material properties and regional hydrological regimes. Most of this data is site specific and would require specific investigation and research to minimise potential errors. Because the seepage component is a small portion of the turnover of water, potential errors may become significant.

The water balance approach has been applied only to the portion of the cover cap over a porebreaking zone as these zones are the most active stores of water for evapotranspiration. All water which passes into the porebreaking zone becomes infiltration to the tailings thus contributing to the seepage flow.

The method used consisted of conducting a water balance on a daily basis, using climatic data covering a period of 9 years. A simple computer program was developed to manipulate the data. Hand methods standard to seepage analysis were used to calculate the slower response effects of the water table.

The model used is a standard moisture budget for groundwater recharge on a daily basis.

$$P = Q + E + \Delta SS + \Delta SG + I$$

where

P = precipitation

Q = runoff

E = evapotranspiration

Δ SS = change in storage of the surface water reservoir

Δ SG = change in storage of the groundwater reservoir (both saturated and unsaturated)

I = infiltration loss to lower zones available for seepage.

The assumptions and basis for calculation are:

Precipitation. Historical data from a nearby raingauge were used. This does not allow for the effects of wet or dry sequences. In a study to determine the design of a cover it would be more appropriate to use simulated data which represent a wet sequence of years, a dry sequence of years and an average sequence of years. Typical rainfall hyetographs are shown in Figure 1.

Evapotranspiration (ET). Actual ET is not directly calculable. More accurate estimates may be derived by carrying out research which monitors the moisture balance at short intervals over a significant period of time. Such estimates require lysimeters, trial plots, plant pots etc, established with the proposed vegetation and at all stages of growth. This study has taken a simplified approach which is coarse in its application.

Potential ET was calculated using formulae which utilise empirical correlations between ET and climatic factors. The potential ET so derived was compared with the average annual evaporation for a class A pan and from this a pan factor was calculated. The pan factor was then applied to the daily class A pan evaporation data, averaged over the month, to give an estimate of the potential ET.

The actual ET is a portion of potential ET and is dependent on the unsaturated soil moisture properties of the soil, the moisture supply and the vegetative factors, such as plant type and stage of growth. In this example assumptions were made so that

- above a moisture content of 25 per cent voids actual ET = potential ET
- below a moisture content of 25 per cent voids actual ET = 0.
- actual ET applied equally through the soil zones (ie root zones penetrate whole soil zones to the pore breaking zone).

This assumption means that, for this example, vegetation behaviour is completely dependent on the soil moisture availability.

Misiture content equivalent to 25 per cent voids marks the level when plants are assumed to permanently wilt with zero transpiration and evaporation is zero also.

Change in storage of the groundwater reservoir. Soil consists of solids and pores, the pores are generally available for storage and transfer of moisture. The important parameters for unsaturated soil are the amount of soil suction the soil is able to exert on moisture and the hydraulic conductivity of the soil. Both these are dependent on the degree of saturation of the soil. With increasing moisture content the soil suction decreases and the hydraulic conductivity increases until it reaches the saturated hydraulic conductivity or permeability. A rigorous study using these properties (illustrated in Fig 2) requires a detailed study of specific soils at specific compaction values, to give the type curve, soil moisture vs parameter, and then an iterative calculation would be required. An example of this approach is shown in NUREG/CR-3078 (1983).

For this example simplifying assumptions have been made as below.

- The surface is relatively flat so that the rate of infiltration is greater than potential precipitation during the period the soil is not saturated.
- The hydraulic conductivity is sufficient to distribute moisture evenly through the zones and has a maximum value equal to the permeability of the zone.

Change in storage of the surface water reservoir. The behaviour of the surface water reservoir is dependent on the rate of precipitation and the state of the underlying soil moisture. The simplifying assumptions, for this example, are

- runoff and storage in the surface water reservoir = 0 whilst the underlying soil is unsaturated

- when the soil is saturated the precipitation for 1 day increases the depth of the storage by the amount of the precipitation (mm). Moisture is lost from this storage at the rate of potential ET plus the infiltration loss to lower zones. The balance is available for ponding or for runoff depending on the mode under consideration

- if the mode is external drainage, - ie promoting runoff, the example considers the balance derived above to runoff at the end of the period, - ie each new period starts with zero surface storage. This assumption does not take into account the surface depression effects which may be built into the surface layers (either deliberately, or accidentally by influences such as settlement of tailings). Techniques such as the 'rational method' could be used to modify the runoff component of this example

- if the mode is internal drainage, ie promoting a pond on top of the cover, the balance derived above is added to the previous depth of the pond. The pond will continue to grow larger as long as precipitation is greater than ET plus infiltration losses.

Infiltration loss to the lower zones. This is the source of seepage. In the guideline on Tailings Impoundment for Uranium Mines the cover systems considered are such that the soil zones are underlain by a relatively high porosity layer, ie porebreaking zone. The implications of this zone are significant not only in preventing the upward movement of moisture plus solutes into the cover, but also as a hydraulic disconnection of the cover soils from the underlying tailings. The fine grained cover soils will have higher soil suctions than the porebreaking zone until the unsaturated soil becomes saturated. This means that all moisture is held in the groundwater reservoir (plus the surface water reservoir) until the soil becomes saturated. Only on saturation will moisture move into underlying porebreaking zones under gravity.

This example assumes:-

- $I = 0$ whilst soil moisture is less than 100 per cent pores;

- $I = K'iA$ (Darcy's Law) for soil moisture at saturation where K' is the effective (weighted) permeability across the soil zones and i is the hydraulic gradient across the same zones (always greater than 1).?

In summary, the model used for this example uses on a daily basis a soil moisture budget:

$$P = Q + E + \Delta Ss + \Delta SG + I \text{ (all in mm/unit area)}$$

with the following assumptions

P = daily rainfall

whilst upper zones are unsaturated

$\Delta SS = 0$

$Q = 0$

$I = 0$

when upper zone saturated

$I = K'iA$

$\Delta SG = 0$

for internal drainage case (pond)

$Q = 0$

for external drainage case (runoff)

$Q = P - E - I$

for soil moisture greater than 25 per cent voids

E = E potential = pan factor x pan evaporation

for soil moisture at 25 per cent voids

$E = 0$

Climatic data of precipitation and pan evaporation were used to determine the behaviour of a cover of standard zoning in which the study considered varying thicknesses of the zones.

The cover considered consisted of a low permeability zone overlain by a porebreaking zone which was covered by random soils and a surface layer of top soil. The topsoil was considered to be loosely placed, the random soil and filter to be compacted to moderate density and the porebreaking zone to be of high porosity. Table 1 shows the parameters assumed.

TABLE 1. SOIL PARAMETERS

	Loose Soil	Compacted Soil	Pore-breaking zone	Impermeable zone	Tailings
porosity(n) (per cent)	62	28	28	28	52
Vertical permeability (Kv) (cm/s)	$1x10^{-2}$	$4x10^{-7}$	$1x10^{-2}$	$4x10^{-7}$	$3x10^{-6}$
Dry unit weight (γd) (KN/m^3)	9.8	18.6	18.6	18.6	12.0

TABLE 2. THICKNESSES (MM) FOR TOTAL SOIL OVER POREBREAKING ZONE

	500	1000	2000	3000	4000	5000
Gravelly Topsoil	200	300	300	500	500	500
Random Rock Soil	300	700	1700	2500	3500	4500

Typical output for four of the 108 cases studied is shown at Figure 1. This shows the daily precipitation, calculated potential ET, fluctuation in soil moisture for two different years with (i) a 500 mm soil thickness draining to the parameters, (ii) a 500 mm soil thickness draining to the centre with no runoff permitted, (iii) a 3000 mm soil thickness draining to the centre with no runoff permitted and (iv) case (iii) subjected to a wetter rainfall season.

From this water balance study based on the behaviour of a flat horizontal surface it was possible to develop a relationship, for the site specific climate and soil data, between the thickness of the soil zones in the cover and average values for:

- the actual evapotranspiration
- the days of growing vegetation on the cover
- the days of moisture stress (wilting) of vegetation on the cover
- the infiltration through the cover to seepage
- the days of saturation of the soil cover and
- the volume of runoff

as ratios of the total precipitation or the period for the two cases where:

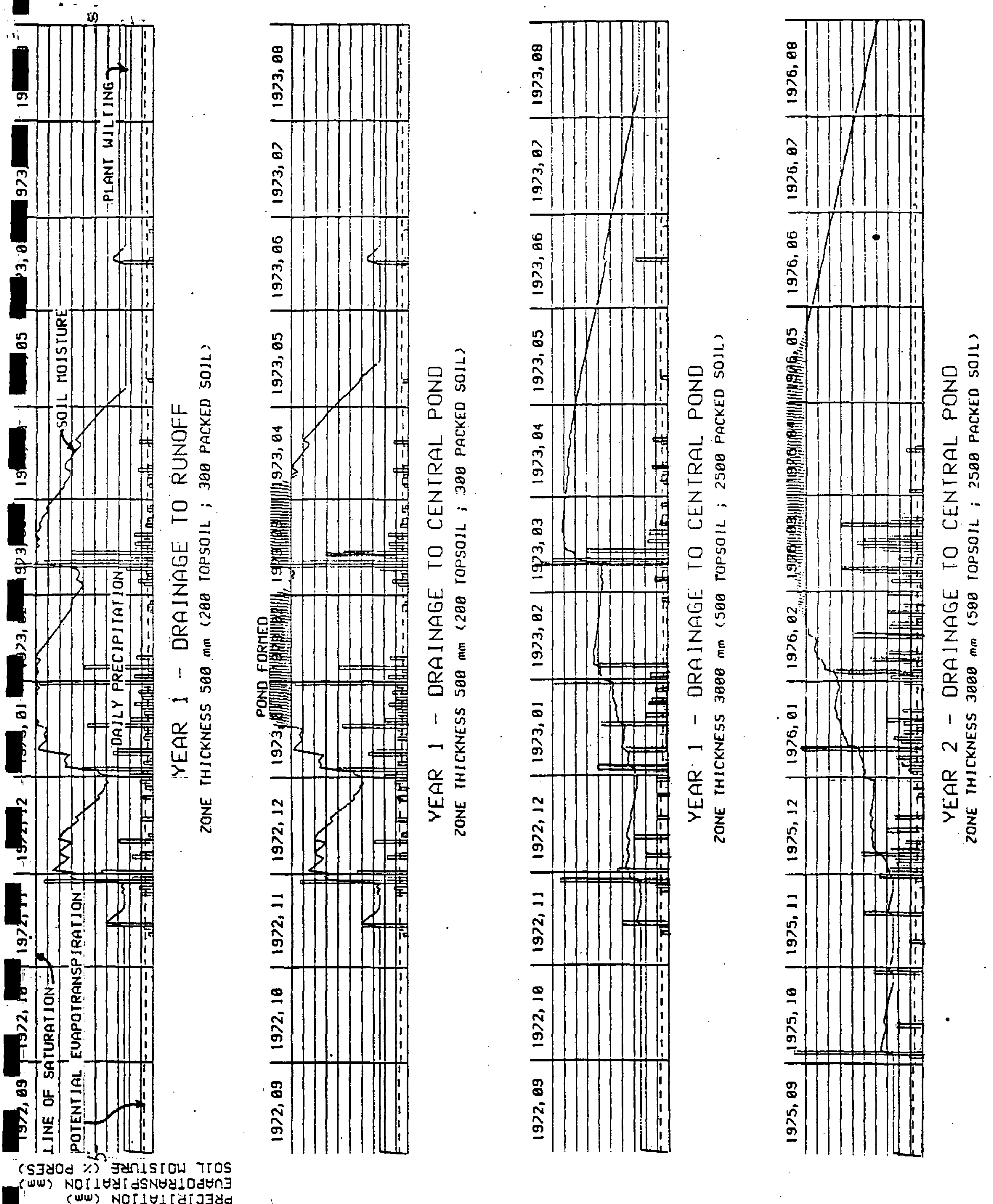
- the cover was designed to shed runoff outside the catchment and
- the cover was designed to form a pond within the catchment, see Fig. 3 and Fig. 4.

This study showed that, for the site specific factors considered, the thickness of the soil zones above the pore breaking zone of the cover structure has a major effect on the amount of infiltration to seepage and the viability of the vegetative cover up to a thickness beyond which further increases in thickness have a lesser effect.

It was also noted that thick covers have less variability in behaviour between years than thin covers, see Fig. 5.

Drainage to pond has a much greater infiltration to seepage than drainage to runoff. However drainage to runoff presents both a greater erosion potential and a lesser soil moisture availability for sustaining vegetative growth.

The provision of a zoned cover cap over a decommissioned tailings impoundment has a significant influence on the amount of seepage which will move into the groundwater. A comparison was made with a study carried out to predict seepage at the end of the operational phase of a similar impoundment and it was found that the capping thickness had a significant effect as shown in Fig 3. For the external drainage case seepage varied from 10 per cent down to 0.1 per cent of maximum predicted operational seepage whereas the internal drainage case varied from 100 per cent down to 1 per cent dependent on the thickness of cover soil.



EXAMPLE 1 - COVER SOIL ZONES

WATER BALANCE, SOIL MOISTURE STORAGE, PONDING, RUNOFF, PLANT GROWTH, ETC.

Figure 1

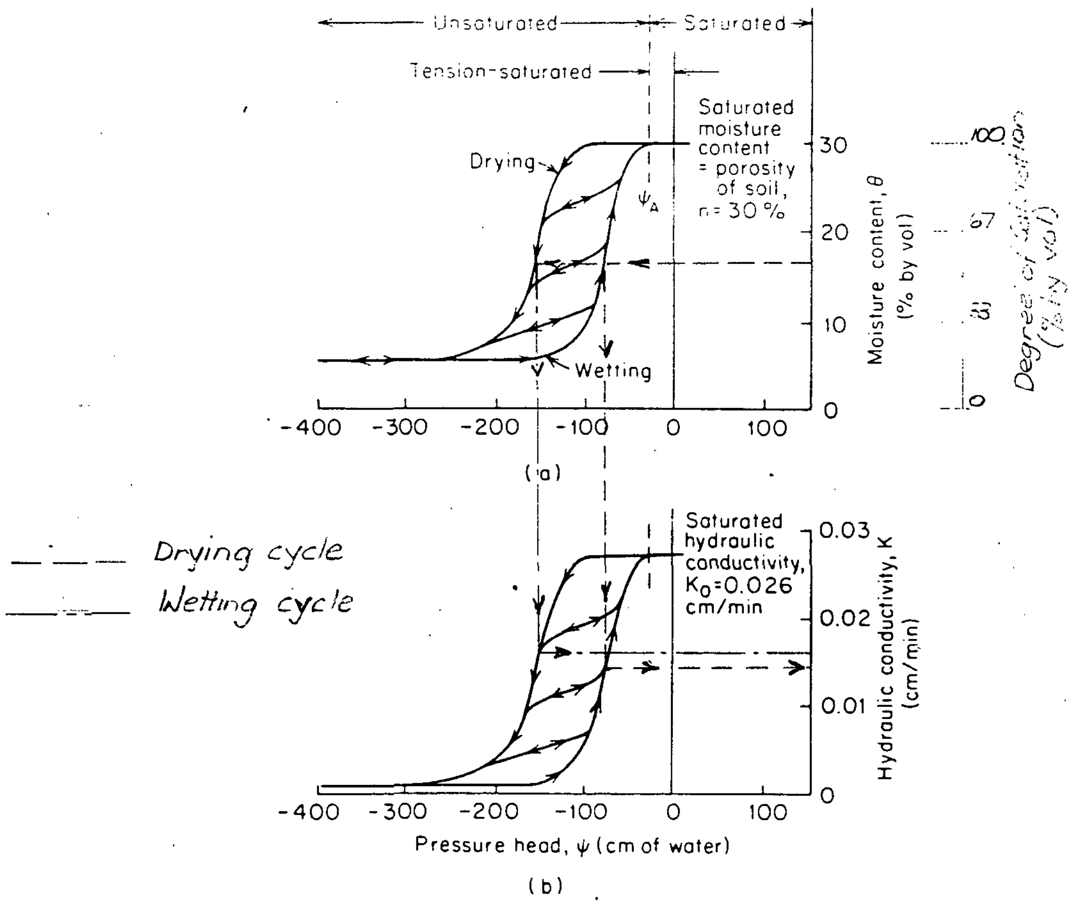


Figure 2. Characteristic curves relating hydraulic conductivity and moisture content to pressure head for a naturally occurring sand soil (after Liakopoulos, 1965a).

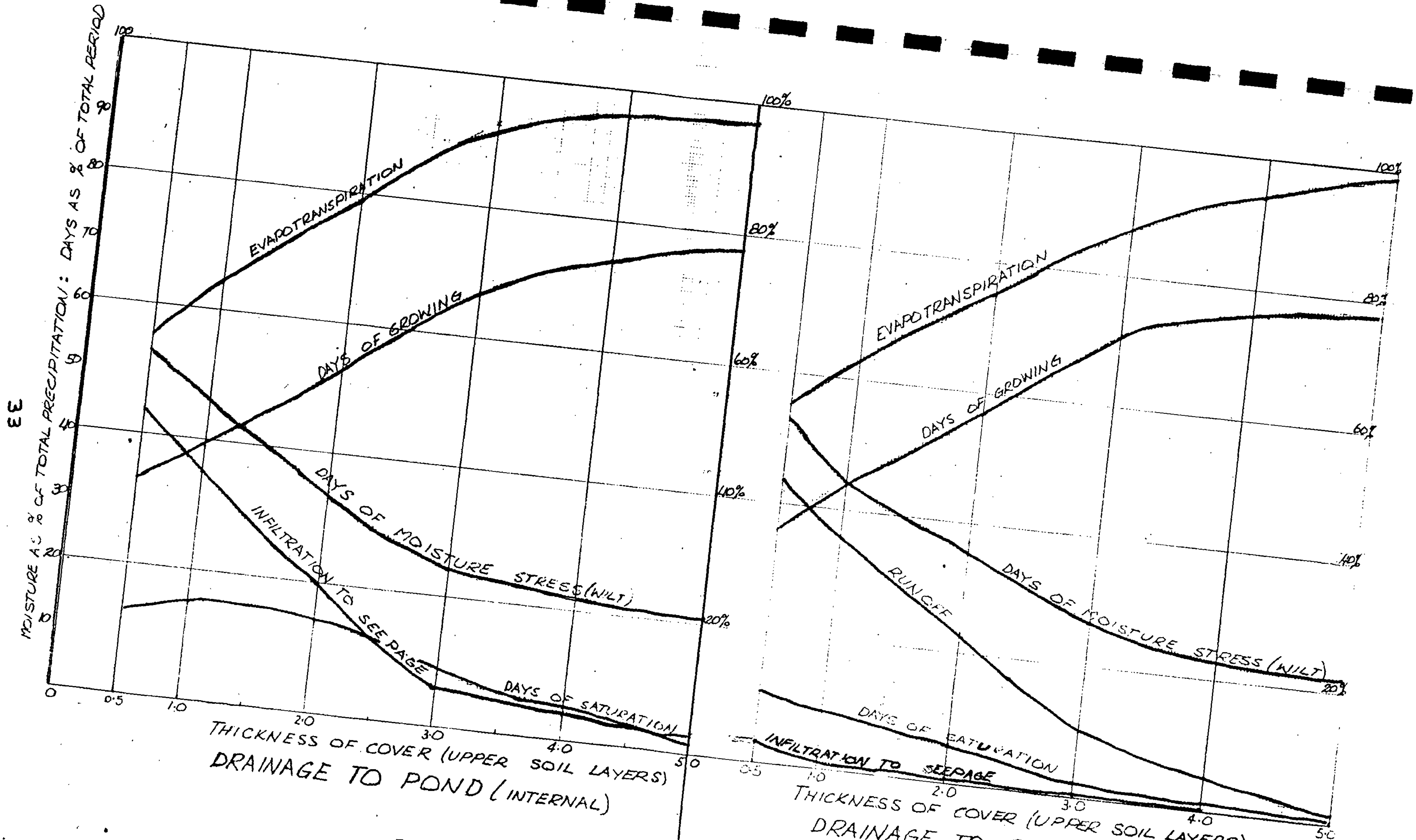


Figure 3 STUDY OF MOISTURE / THICKNESS RELATIONSHIPS FOR TROPICAL CLIMATE, ZONED COVER (9 YEARS OF DATA)

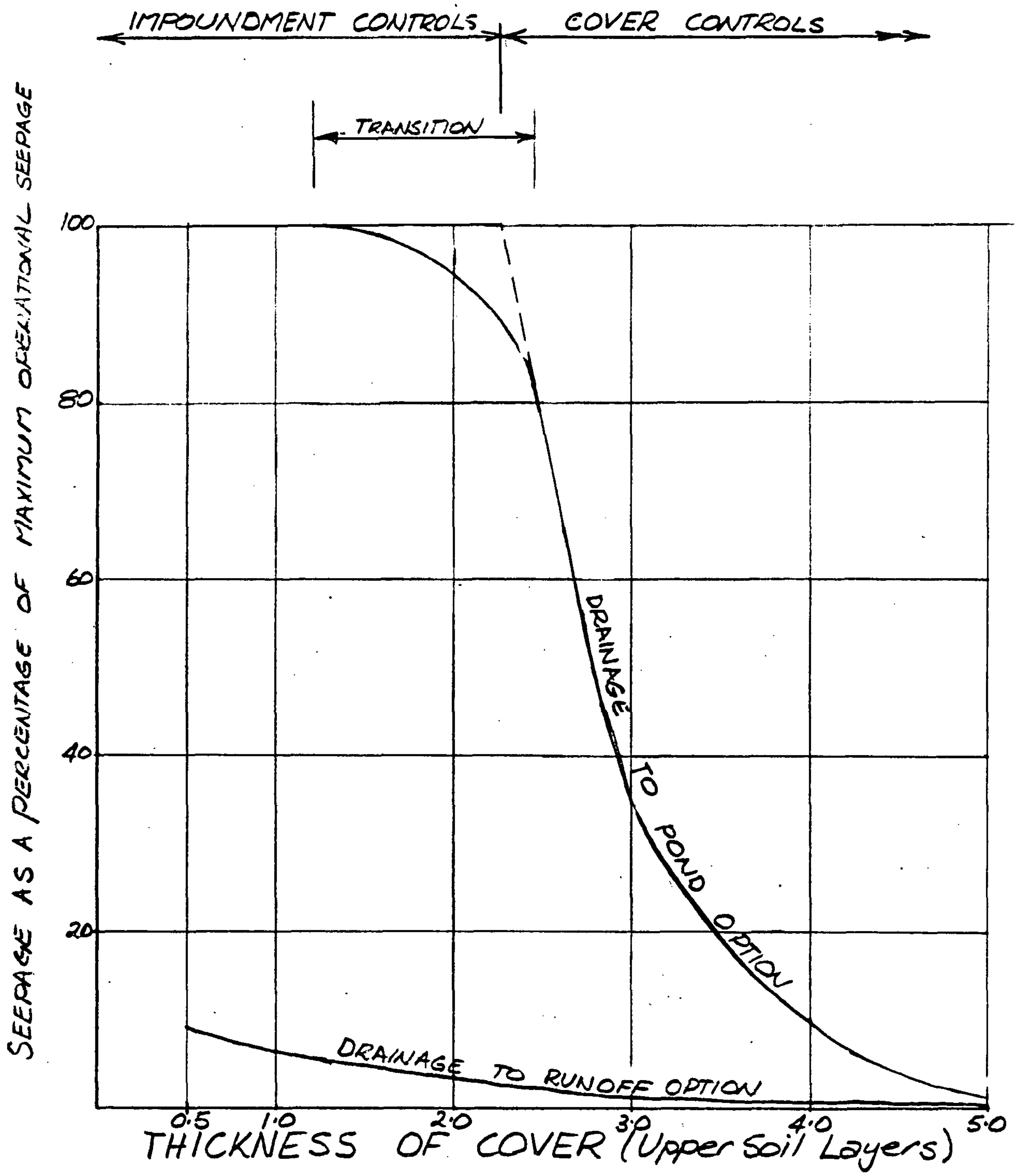


Figure 4
COMPARISON OF COVER DRAINAGE OPTIONS WITH MAXIMUM OPERATIONAL SEEPAGE

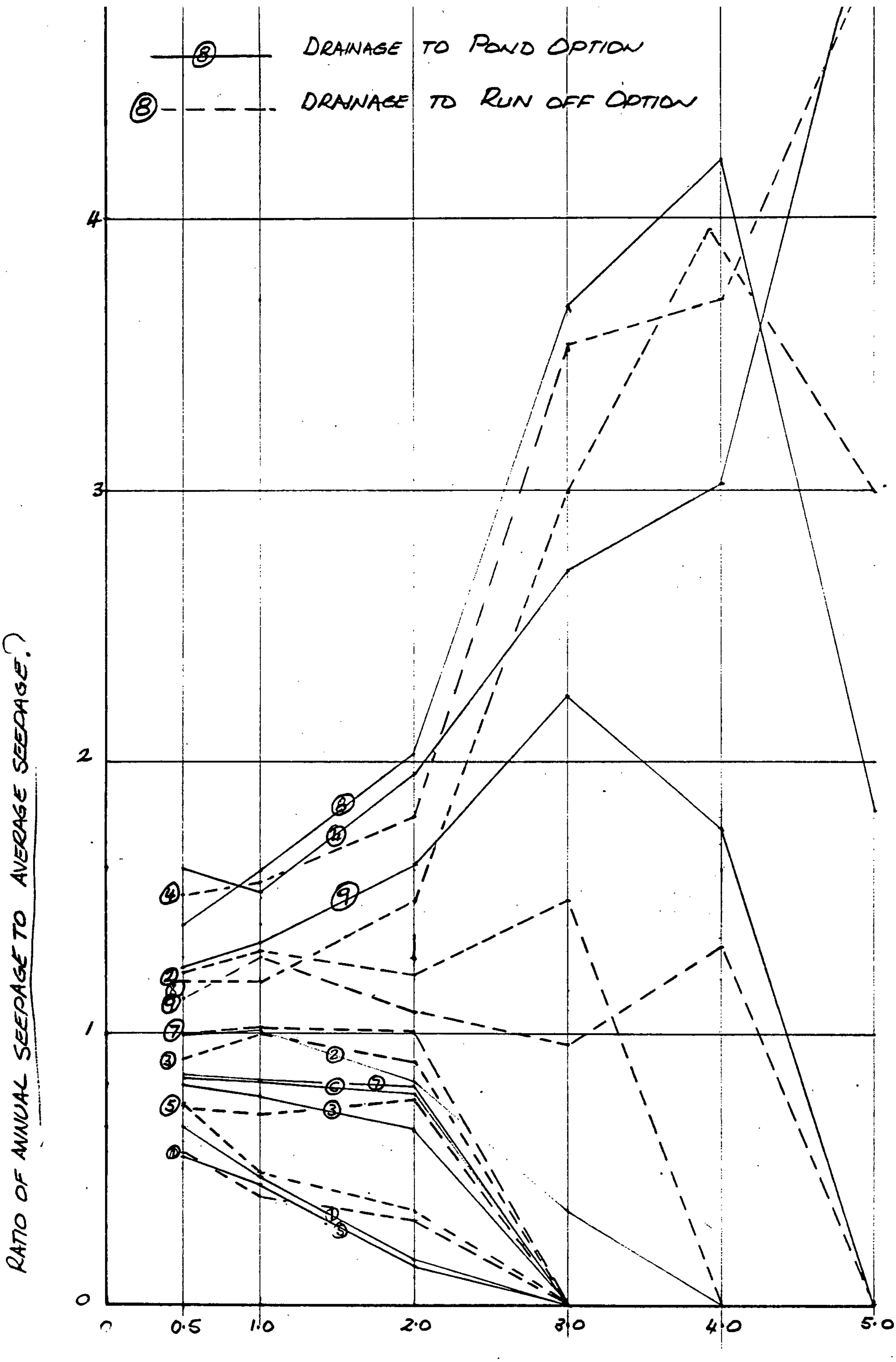


Figure 5. THICKNESS OF COVER.

VARIATION OF SEEPAGE WITH DEPTH.

APPENDIX IV

PROCESSES AND ESTIMATION OF SOIL EROSION

Processes of Soil Erosion by Water

Soil erosion by means of water involves the detachment of soil particles from the parent material, its transport by flowing water and subsequent deposition. Soil detachment mechanisms include:

- raindrop impact;
- shearforce action of flowing water and silt;
- slaking (action of some saturated soils disintegrating);
- wind, heat and frosts in dry periods break up unvegetated soils; and
- human mechanisms such as heavy equipment.

The operation of these mechanisms is dependent on the soil types that are encountered in a particular area.

Soil particles are then transported primarily through channelised runoff of surface water. Surface runoff occurs when rain of sufficient quantity and intensity exceeds the infiltration rate of the soil and the volume of surface depressions. The quantity of soil transported becomes a function of the quantity of water, the velocity turbulence and depth of the water. As the water moves over the soil and down the drainage lines it will carry with it detached soil particles and these in turn will cause further detachment of soil along the water-flow route. When the velocity is reduced (eg by changes in gradient, rainfall intensity or channel geometry) deposition will occur.

Factors Controlling Rate of Erosion

The rate of erosion depends on

- soil properties such as infiltration capacity (permeability), depth of soil, particle size distribution, soil structure;

- topography (slope, length and gradient);

- vegetation; and

- climate, including spatial and temporal distribution of rainfall.

These various factors interact with each other in that erosion resistant soils can be eroded when found with little vegetation, on steep slopes or in areas with high intensity rainfall, whereas highly erodible soil under good vegetation, gentle rainfall intensities and on slight reliefs can have no erosion.

Erodibility of soil is a complex property measuring the capacity of soil to resist detachment and transport by rainfall and runoff. Generally soil erodibility increases with greater silt content and decreases with greater sand, clay and organic matter contents. The amount of surface runoff is very dependent on the infiltration capacity or permeability of soils and soil erodibility and runoff increase as permeability decreases. Movement of soil particles is substantially controlled by surface movement of water. Tables 1, 2, 3 and 4 indicate threshold velocities for a number of different soils, various particle sizes, surface slopes and grassed vegetation.

Changed Rates of Runoff

The change in land use from its natural state to a mining operation causes a change in the runoff rates. The type of water management system chosen and the climate of the region dictate the degree of change. In rehabilitation an attempt to stop infiltration into the tailings as well as possibly into the waste rock dumps will possibly increase the total runoff from the project area.

Aspects that have to be considered are that if maximum peak flow rates are increased due to an increase in impervious areas, reduction in time of concentration and/or concentration of flows, then greater erosion will occur downstream. Another aspect is that the frequency of peak discharge rates of a given magnitude can increase thus causing lack of recovery of vegetation on the banks of water courses with a subsequent increase in the width and depth of the waterway.

Predicting Erosion Rates

The potential soil loss rate from a particular site can be assessed by using the Universal Soil Loss Equation (Wischmeier and Smith, 1978). This method is only an empirical approximation which enables an order of magnitude estimation of the potential problems and the relative effect of the various factors involved. Moreover, it is based on American conditions and has yet to be modified for Australian conditions. The increase in erosion due to a mining activity or the reduction due to rehabilitation can be calculated using this equation:

$$E = R.K.LS.C.P.$$

where:

E = computed soil loss in t/ha (dry weight) for a given storm period

R = rainfall erosivity index for the given storm period in mt/ha x 30 min. max. intensity in cm/h.

K = soil erodibility factor in t/ha per metric unit of R. Different soil horizons will have different K factors.

LS = combined length/slope factor allowing for the length and slope of the area under consideration.

C = soil cover factor.

P = soil practice factor for a disturbed soil and is allocated the factor of 1.

Methods of estimating the various factors are outlined elsewhere (Vanomi, 1975; Garvin et al, 1979; Israelson, et al, 1980).

The Universal Soil Loss Equation estimates soil losses on an annual basis and has been used extensively for agricultural and conservation pursuits in the United States. More recently a Modified Universal Soil Loss Equation has been developed (Simons, Li and Associates 1982, Walters, 1983) to determine sediment yields based on single storm events. However, no empirical calculation can substitute for actual field measurements of erosion rates which allow assessment of mining impact and evaluation of effectiveness of any rehabilitation procedures undertaken. A programme of an approach adopted in the Alligator Rivers Region of the Northern Territory in this regard is given by Duggan (1982, 1983).

Wind Erosion

Wind is an important erosion agent particularly in arid and semi-arid areas where temperatures, evaporation and wind speeds are high. The rate of wind erosion is dependent on such factors as wind velocity, fetch, moisture content of soil, particle sizes, surface roughness and vegetative cover (Marshall, 1972).

The movement of soil surface particles by wind occurs in three overlapping categories (Bagnold 1941) including surface creep, saltation and suspension. Surface creep is the action of larger heavy particles rolling across the soil surface due to wind. Saltation is the action of less heavy particles bouncing across the surface being propelled forward by the force of the wind. The higher these particles bounce the greater the forward momentum becomes due to the higher velocity airstream into which the particles had ascended. These transported particles cause abrasion which is the wearing away of solid materials by the impacts of the transported particles, and is considered to be the primary phase of the wind erosion process. The longer saltation continues, the greater is the quantity of erodible material formed by abrasion and the higher the rate of soil discharge. The saltation process also abets wind erosion because it tends to destroy vegetation thus exposing more source material to wind action. Saltation gives rise to the movement of finer particles of 0.02 mm diameter and smaller. These fine particles are light enough to remain suspended in the atmosphere and this movement is referred to as suspension.

Erodibility of Soils due to wind

Climate is a most important parameter for wind erosion as it has been shown that moist soils are not readily erodible by wind (Chepil 1956). Wind erosion therefore dominates when strong winds and dry soils coincide which is typical in the arid regions in Australia.

Soils that are most susceptible to wind erosion are those which have weak aggregate stability and therefore can be broken down easily. Any soil that has a high percentage of either coarse (2mm) or fine (0.05mm) sand sized particles is highly erodible. Marshall (1972) has stated that a high percentage of particles smaller than the fine sands or greater than the coarse sands is more resistant to erosion.

Accelerated wind erosion can result from the effects of grazing animals in breaking up the soil aggregates and exposing underlying soil profiles to direct wind action.

The threshold drag velocity (U_T) can be calculated for different particle size diameters (d) and densities (g) by an expression due to Bagnold (1941).

$$U_T = A_B \left[gd\,(\rho_s - \rho_a)/\rho_a\right]^{1/2}$$

Where A_B = Bagnold Coefficient (= 0.1 for particle sizes <0.2mm)
ρ_a = density of air
ρ_s = density of particle

and these relationships are shown in Figure 1.

Vegetation is an important parameter in the erosion process and before any appreciable wind erosion can occur an inadequate cover of vegetation is required, therefore the obvious solution, to avoid wind erosion is an adequate vegetation cover if climate permits.

The force of wind near an erodible surface is reduced by any surface obstructions such as rocks, stones, plants and plant remains to such an extent that prevention of wind erosion can occur. Marshall et al (1978) showed that scattering rock fragments on slime dump surfaces at Kalgoorlie controlled dust movement by wind from the dumps.

Long term erosion prevention therefore must consider armouring if vegetation growth will become suspect due to unfavourable climatic conditions.

Predicting Wind Erosion Potential

A soil loss equation developed by Chepil and co-workers (Chepil and Woodruff 1963); Israelsen et al 1980) can be used to predict wind erosion potential:

E = I.C.K.V.L.

in which

E = soil loss in t/ha/year

I = soil wind erodibility factor (soil type plus exposure to dominant wind)

C = local wind erosion climatic factor

K = soil surface roughness factor

V = vegetative factor, and

L = length of the unshielded distance parallel to wind in the direction of the wind fetch.

Each of these factors is based upon relatively simple measurements of site-specific soil and environmental characteristics, including the following:

- mean wind velocities and predominant direction;
- unshielded wind fetch distance;
- windward knoll effect (exposure of slopes to wind);
- percentage of soil particles larger than a specified size;
- mean height of individual roughness elements in cover material;
- mean annual precipitation;
- mean annual temperature; and
- density of vegetative cover (organic matter per unit area).

Tables, graphs, and maps have been developed relating these parameters to the factors in the soil loss equation for the US (see Israelsen et al 1980).

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TABLE 1: ALLOWABLE VELOCITIES IN GRADED DIVERSION CHANNELS (FROM VANOMI, 1975)

Soil Texture	Velocity (m/sec)			
	Bare Channel	Vegetation		
		Poor	Fair	Good
Sand, silt, sandy loam, silty loam	0.46	0.46	0.61	0.91
silty clay loam, sandy clay loam	0.61	0.91	1.2	1.5
clay	0.76	0.91	1.5	1.8

TABLE 2: MAXIMUM ALLOWABLE VELOCITIES TO AVOID SCOUR (STEPHENSON, 1979)

Material	dg (mm)	Velocity (m/sec)
Fine silt	0.01	0.17
Fine sand	0.1	0.24
Medium sand	1.0	0.55
Gravel	10	1.0
Pebbles	100	3.0

TABLE 3: PERMISSIBLE VELOCITIES FOR VARIOUS SOILS (GARVIN ET AL, SOIL CONS. VICTORIA, 1979)

Bare Earth	Velocity (m/sec)
Sand	0.4
Sandy loam	0.5
Silty loam	0.6
Stiff clay	1.2
Fine gravel	0.8
Coarse gravel	1.2

TABLE 4: PERMISSIBLE VELOCITY FOR VARIOUS SOIL AND VEGETATION (GARVIN ET AL, SOIL CONS. VIC. 1979)

	Velocity (m/sec)							
Vegetation Grass	Kikuya			Bent, Couch, Fescue Grass Mixtures				
Slope per cent	0-5	5-10	10+	0-5	5-10	10+	0-5	5-10
Erosion resistant soils	2.5	2.2	2.0	2.2	2.0	1.8	1.5	1.0
Erosion susceptible soils	2.2	2.0	1.8	2.0	1.8	1.5	1.2	0.8

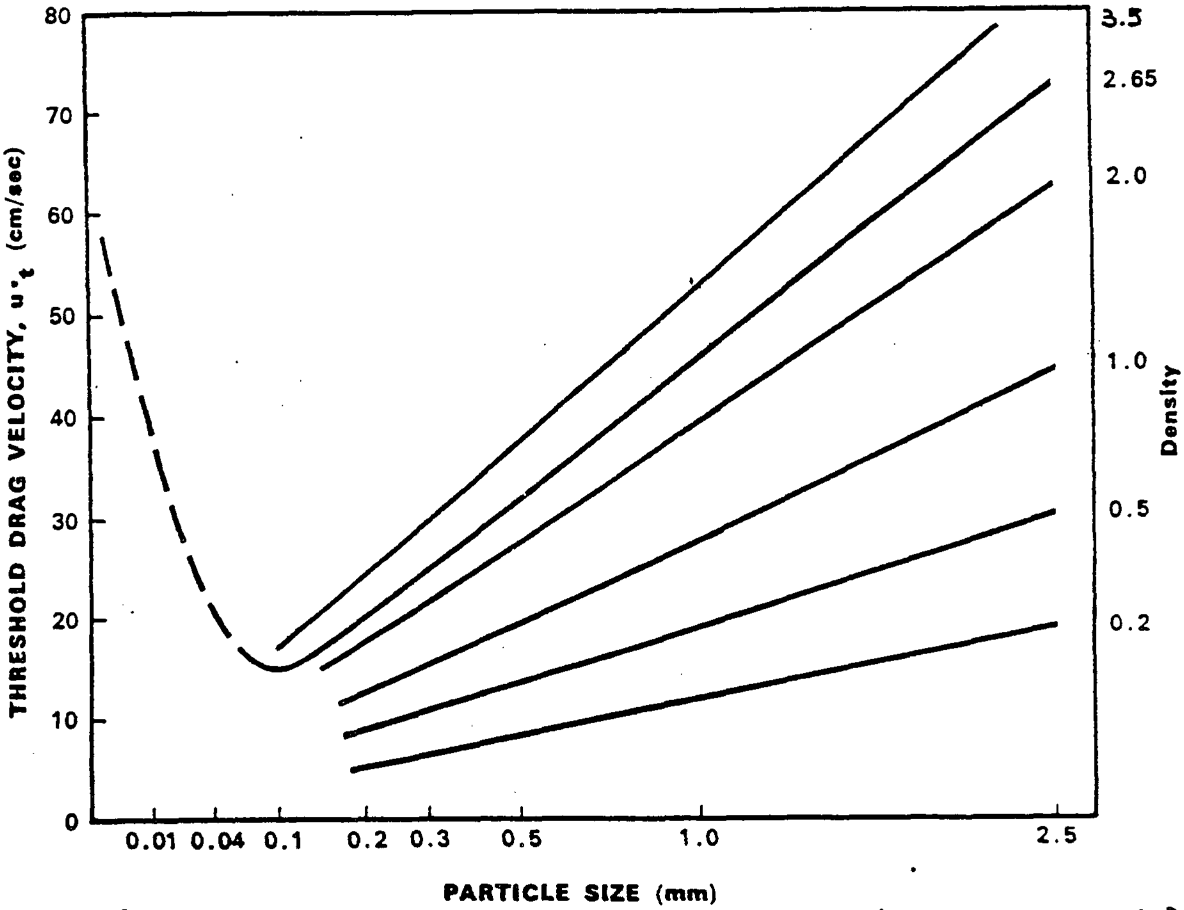

Figure 1 (From Marshall, R.K Principles of Soil Erosion and its Prevention AGPS 1972)

Relationship of the drag velocity of the wind required to move particles of varying size and density. From the figure it can be seen that particles of about 0.1 mm in diameter require the lowest velocities of all to be set in motion; particles smaller and larger than this require higher velocities to move them. Consequently, soil with a predominance of particles of the most susceptible size are the most easily erodible. Also, particles of different density vary greatly in the velocities required to set them in motion. Quartz (sand) particles, of density 2.65 are relatively much less susceptible to movement than the lightest organic matter particles (density 0.2). Reduction of wind velocity must therefore be much greater if it is of importance to retain organic material at a site than if it is only necessary to retain quartz particles. drag velocity is very approximately 1/10 of actual mean wind speed. (Source used in compilation: Bagnold, R. A. (1941) *The physics of blown sand and desert dunes.* Methuen, London, 265 pp.)

APPENDIX V

SOIL MANAGEMENT IN MINE REHABILITATION

The need for soil retention in a mine rehabilitation plan can be determined by: (1) surveying the lateral and vertical variation in soils, weathered rock and waste rock, (2) characterising the properties of these materials in the laboratory, (3) assessing the materials' growth limiting factors under glasshouse conditions and (4) determining the techniques for establishment and maintenance of a stable vegetative cover in the field. Although such a program can be undertaken at any stage during the life of the mine, there are advantages to mine planning if this research can be started prior to mining.

TABLE 1: SURVEY OF SPATIAL VARIATION IN POTENTIAL GROWTH MEDIA.

Medium	Action Required
Soil	Examine existing soil data. Undertake soil survey. Sample surface and subsurface horizons of each of the soil types identified.
Weathered Rock	Examine existing regional geological data. Analyse mine bore-hole logs to determine spatial variation in rock type and degree of weathering. Obtain core and/or chip samples of each overburden type.
Waste Rock	Sample fresh and weathered material before and after recontouring.

The steps involved in the survey of the nature and extent of potential growth media are summarised in Table 1, and the methods suitable for laboratory characterisation of the chemical and physical properties of the media are listed in Tables 2, 3 and 4. It can be expected that these methods will be progressively altered. The nature of glasshouse studies to assess the magnitude of growth limiting factors are briefly summarised in Table 5. Similar trials can be conducted in the field, but assessment of the establishment and development of native and/or exotic species is usually made in large plots over a period of several years. The efficiency of the vegetative cover in promoting landscape stability can also be monitored on the mine site via erosion studies in which runoff and soil movement are quantitatively assessed.

Table 2. Chemical laboratory tests for assessing nutrient availability in soils and mine wastes

Element or property measured	Units	Extracting solution	Suggested critical* values	Priority**	Other comments
pH		H_2O (1:5)	5.5-8.5	1	Toxic levels of Al may occur at pH <5.0
"		0.01M $CaCl_2$ (1:2)	4.8-7.5	2	
Organic C	%	$K_2Cr_2O_7/H_2SO_4$		1	Normal soil range is from 1 (low) to 5 (high)
Total N	%, μg/g	H_2SO_4/K_2SO_4		2	Normal soil range is from 0.06 to 0.5%
Mineralizable N	μg/g	1M KCl after incubation		2	
NH_4-N	"	1M KCl		2	Generally low in well aerated media
NO_3-N	"	"		2	
P	"	0.5M $NaHCO_3$	10	1	Good for acid and alkaline media
K	meq/100g	1M NH_4OAc	0.2-0.3	1	Measure of exchangeable cations if allowance made for soluble cations
Ca	"	"	1.2	1	
Mg	"	"	0.4-0.8	1	
Na	"	"		1	
Ca, Mg, K, Na	meq/l	H_2O (saturation extract)		2	
CEC***	meq/100g	1M NH_4OAc		2	
"	"	0.002M $BaCl_2$		2	Use on solids high in iron and aluminium oxides
SO_4-S	μg/g	0.01 M $Ca(H_2PO_4)$	15	1	
Fe	"	0.005M DTPA†	2.5-4.5	1	
Mn	"	"	2	1	Toxicity possible if > 50 μg/g and pH acid
Cu	"	"	0.2	1	
Zn	"	"	0.5-1.0	1	
Cl	"	H_2O	<200-600	1	Sensitive species affected by 200 μg/g
B	"	Hot H_2O	1-5	1	<1 μg/g deficient; >5 μg/g toxic
"	"	H_2O (saturation extract)	0.5-10	2	<0.5 μg/g satisfactory for all plants; >10 μg/g even tolerant species affected.

*For nutrients this is the value below which a plant response to the application of the element might reasonably be expected. Most values determined for improved crop and pasture species; critical values for native species will be lower.
** 1 = essential, 2 = desirable in some circumstances.
*** CEC = cation exchange capacity; † DTPA = diethylene triamine pentaacetic acid.

Table 3. Chemical laboratory tests for assessing nonnutrient limitations to plant growth in soils and mine wastes

Element or property measured	Units	Method	Suggested critical value	Priority*	Other comments
			Salinity and alkalinity		
pH		H_2O (1:5)	<8.5	1	Micronutrient and P availability decrease rapidly above 8.5
"		0.01M $CaCl_2$ (1:2)	<7.3	2	
Salinity	mS/cm	E.C. (saturation extract)	2-8	1	Large range in species tolerance
Ca, Mg, Na, K	meq/l	H_2O (saturation extract)		2	Useful for assessing cation balance
CO_3, HCO_3, SO_4 Cl, NO_3	meq/l	"		2	
S.A.R.**		"		1	Determine from concentrations in saturation extract
ESP	%	Direct or from SAR	<15-40	1	Range in plant tolerance to Na difficult to separate physical effects
			Acidity		
pH		H_2O (1:5)	>5.5	1	Levels of Al, Mn and other metals increase rapidly under acid conditions
"		0.01M $CaCl_2$	>4.8	2	
Total S	%	Na_2CO_3 fusion or Ignition in induction furnace		2	Normal soils contain 0.01 – 0.02%S. High values indicate presence of sulphides such as FeS_2.
Sulphides	%	HNO_3 oxidation		2	Is a measure of total potential acid production.
Acid neutralizing capacity	meq/g	Titration		2	Measure of basicity capable of neutralizing acid from sulphides
Lime requirement	meq/g	Titration or incubation with $CaCO_3$		1	Measure of base required to neutralize active acidity.
			Toxic Elements		
Heavy metals	µg/g	0.005M D.T.P.A.		2	
"	"	Total analysis		2	Total analysis only useful if used in conjunction with pH
B	"	Hot H_2O	5	2	
"	"	H_2O (saturation extract)	0.5-10	2	
Se	"	Hot H_2O	1	2	

* 1 = essential, 2 = desirable in some circumstances.

** Sodium adsorption ratio = $Na/\sqrt{(Ca + Mg)/2}$ (concentrations in meq/l)

Table 4. Laboratory tests for assessing physical limitations to plant growth in soils and mine wastes

Property measured	Units	Method	Priority*	Comments
Particle size distribution	%	Clay and silt by sedimentation; sand and coarser fragments by sieving	1	Guide to water holding capacity, permeability and chemical fertility.
ESP	%	Direct or from SAR	1	Critical level for dispersion may be as low as 6 (Northcote & Skene 1972)
Dispersion index		Dispersion of wet and dry aggregates in water	2 2	Can be used in field or laboratory Extends Emerson test to estimate sodicity
Mineralogy		X-ray diffraction	2	Clay mineral type influences medium stability
Water characteristic curve	g H_2O/100 g solid at a given potential (bars)	Pressure plate apparatus and tension table	2	Can be used to determine the pore size distribution in non-swelling materials
Water content				
- field capacity (=0.1 bar)	"	Pressure plate apparatus	1	Can measure on soil allowed to drain for 24 hours
- wilting point (=15 bar)	"	Pressure place apparatus	1	
Available water capacity	%	Difference between water contents at 0.1 and 15 bar	1	Values commonly range from 5% (very low) to 30% (high)
Hydraulic conductivity	cm/hr	Laboratory Field	2 2	Values range from <0.1 cm/hr (very low) to >25 cm/hr (very high)
Unconfined compressive strength	kg/cm^2	Penetration by probe at given water potential	2	No critical value yet established but useful for comparing treatments e.g. gypsum additions.
Bulk density	$g\ cm^{-3}$	Field cores	2	Critical values for root impedance may range from 1.3 $g\ cm^{-3}$ in clays to 1.8 $g\ cm^{-3}$ in sands (O'Connell 1975)
Air filled porosity	$cm^3 cm^{-3}$	Calculation from water content and porosity	2	Should be >0.1 $cm^3 cm^{-3}$ otherwise oxygen supply limited by diffusion (Vomocil & Flocker 1961)

* 1 = essential, 2 = desirable in some circumstances

TABLE 5: GLASSHOUSE ASSESSMENT OF GROWTH LIMITING FACTORS

Limiting Factor	Nature of experiment
Salinity	Leaching trials. Selection of tolerant species.
Specific elemental toxicities	Leaching trials. Amelioration through pH adjustment. Selection of tolerant species.
Nutritional	Identification of deficient nutrients. Characterisation of response curves. Species selection trials.
Physical	Amelioration of surface crusting. Enhancement of available water capacity or air capacity.
Biological	Microbial inoculation trials. Seed viability tests.

To Conserve or Not to Conserve Soil

Soil will normally be used in mining rehabilitation where alternative substrates such as overburden or waste rock cannot support the desired end land use even when treatments costing up to that involved in conserving and replacing soil are applied. However, in uranium mining situations, it may be necessary for the stripped soil to be stockpiled for many years before it is required in rehabilitation works. Consequently both economic and technical data are required to enable the decision on soil conservation to be made (Grundy and Bell, 1981). If the decision is made to save soil, an additional set of management decisions are required to optimally use the soil resource.

Management of the Soil Resource

The properties of soils commonly vary with depth. Even in apparently uniform soils, material lower in the profile may differ markedly in its plant growth characteristics from that at the surface. For example in Australian soils, increases in the levels of salinity and sodicity with depth are particularly common.

On the basis of properties soil horizons can be ranked so that a choice on the selection of each can be made. A number of parameters can be used in this ranking. For example these may be nutritional or they may involve the supply of seed of native species. Microbiological factors are also of importance. The weight placed on these parameters will differ with the envisaged land use. Clearly native seed stocks assume great importance if the aim is a return to native vegetation. This weighted ranking will then determine which of the following systems is applicable.

Use of the whole soil profile - This technique can involve either one of two approaches depending on the relative suitability of soil layers and the desired post-mining land use. Use of the whole profile is usually only advisable if all horizons or depths of the profile are satisfactory or able to be made satisfactory for plant growth. In those situations where first class agricultural land is being mined, a return to original productivity can rarely be achieved without retention of the whole profile.

Soil horizons in order - In this approach, the attempt is to recreate as nearly as possible the original soil profile, and it has a number of advantages, viz. (a) The probability of soil-borne seed reserves being near the surface is high, (b) the A horizon usually has a nutritional advantage over lower horizons, (c) where compaction can be avoided or alleviated, infiltration through the soil should approach the pre-mine condition, (d) to whatever extent is possible the replaced soil should make conditions ecologically similar to the pre-mine condition thus favouring adapted plants and (e) the beneficial soil flora and fauna should be advantaged. The cost of such an approach is liable to be high however, especially if double handling is required. In the latter case, compaction is difficult to avoid, and this can lead to significant reductions in the growth of plants on the replaced soil.

Mixed soil horizons - Where all soil horizons are suitable for plant growth, mixing of the profile during removal and deposition may provide a satisfactory medium for plant growth. In this case, stripping and replacement are uncomplicated and relatively inexpensive, but there is dilution of the beneficial effects of soil organic matter, seed reserves and soil microflora.

Use of selected horizons - The selection of particular horizons ensures that either undesirable material is avoided or maximum use is made of beneficial soil.

Thin surface layers - In most undisturbed situations, the soil seed reserves are concentrated at or near the surface and usually in the top 5 to 6 cm. Consequently collection and replacement of more than the top 5 cm of soil generally results in dilution of the viable seed reserve. The thin layer technique overcomes this effect by covering an adequate depth of satisfactory soil from any source with a thin recently collected surface layer.

A horizon alone - The A horizon is used alone where the B horizon is unsuitable for some reason, eg excess sodium, salinity or poor structural characteristics.

B horizon alone - The use of the subsoil horizon alone is unusual and would only be undertaken where the A horizon was unsuitable for some reason, eg structural breakdown or low water holding capacity.

C Horizon - This material may also be useful in increasing effective soil depth where insufficient acceptable soil is available to cover all of the mined area. It is unusual to find an acceptable C horizon below unacceptable A and B horizons.

Alluvial/colluvial material - Where these have been in place for long periods, they normally develop the equivalent of A and B horizons.

The Mechanics of Soil Removal and Placement

The options detailed above entail varying degrees of precision in the collection of soil. There are also other constraints to be considered in deciding on the methods and machinery to remove and replace soil.

Removal - Many of the constraints relating to removal apply also to soil placement. A particularly important constraint is cost, a factor which is reflected in such concepts as maximum distance of travel for various machines and the varying efficiency of machines for different functions. Soil compaction will vary depending on water content and the machines used. There is an optimum water content at which the risk of compaction is least, and this value can be determined using the Protor compaction test which is a relatively simple laboratory technique.

Other constraints in removal include the off-road mobility of machinery and climatic conditions which compound the factors already mentioned.

For the collection of soil, bowl or elevating scrapers are almost invariably used. With experienced drivers, this equipment is reasonably effective in collecting varying depths of soil. With the newer models working in tandem, it is possible to separately collect and deposit the A and B horizons in order. Scrapers have reasonable off-road mobility, but they are very expensive to run over long distances. However, they cause compaction both in collection and deposition and do not deposit as effectively as they collect soil. Soil can also be effectively stripped by front end loaders or small bucket wheel excavators, but these require a different transport method.

Transport - Scrapers and trucks are the most commonly used means of transporting soil. Again scrapers are the most commonly used as they perform the three operations of collection, transport and deposition. They are not an efficient transporting machine with the maximum distance of travel being commonly from 1.5 to 2 km. Trucks are not as restricted economically but require a smooth hard surface.

Deposition - Equipment considerations are also of great importance in the placement of soil. Scrapers have been proved to be the machines most capable of laying the soil as desired in a cost efficient manner.

They do, however, cause compaction so that some form of ripping may be necessary after the soil is deposited. Ripping may be necessary even in the absence of compaction to ensure vertical drainage, but this may bring to the surface large rocks which pose problems for subsequent planting machinery. Other deposition measures in use include the spreading of stockpiled soil with bulldozers trailing large logs or chains to smooth the surface. This technique is common in the sandmining industry.

Stockpile Storage of Soil

Where soil must be stockpiled, the effect of soil storage in this manner has not been adequately determined. Published reports have documented changes in a number of soil properties, including:

- deterioration of soil structure with a marked decrease in porosity and permeability and an increase in dispersion;
- a decline in soil microbiological properties;
- a decline in organic carbon and cation exchange capacity; and
- a reduction in seedling emergence, species richness and diversity, live plant cover and litter cover.

Stockpiling of soil is more than simple storage, and such factors as: compaction in the machinery processes of collecting the soil, forming the stockpile and spreading soil; the compaction due to the weight of the pile; the type and degree of the original vegetative cover; the water content both at collection and during storage; and the season of collection; will influence soil changes. The studies published to date do not assist in predicting deleterious or possible beneficial effects of stockpile storage.

Notwithstanding these problems, stockpiling of soil is still highly desirable in most situations.

Physical Management of the Replacement Soil

Physical management will usually be directed in two principal directions, viz. the control of erosion and the achievement and maintenance of soil physical conditions that are suitable for plant growth. In conditions where the soil overlies a substrate with adverse properties such as acidity or salinity, measures designed to prevent capillary rise or the lowering of the water table may be required.

Erosion control should be directed at reducing the erosive force of water through such measures as a reduction in the length and degree of slopes, the provision of benches and batters and contour cultivation (including contour banks, basin listing, etc), and in lowering the erodibility of the soil surface. The latter can be achieved through the use of mulches such as straw, woodchips, brush matting, water-soluble bituminous compounds or plastic meshes. Soil may be keyed into the spoil with ripping. Cover crops may be employed.

The degree of preparation of soil for plant growth will range from ripping to ensure infiltration to the provision of a "soft" agricultural seedbed and is dependent on the desired vegetative cover. Where the exchangeable sodium percentage is high, the application of gypsum may reduce crusting, and the application of mulches may also be helpful.

Nutritional Management of Replaced Soil

The objective of nutritional management is to correct nutrient deficiencies and to alleviate chemical toxicities. Chemical characterisation of the soil should ensure that material with toxic elements or excess salinity should be avoided so that amelioration, at least initially, should not be necessary. Where amelioration is necessary, leaching via irrigation may be practicable.

The diagnosis and correction of nutrient deficiencies can be complicated but a systematic approach can be used to assess fertiliser requirements. For all species, both establishment and maintenance requirements should be determined, and this may require long-term monitoring of rehabilitated areas. There is also a need to distinguish between species in their requirements. Native species may have far lower nutrient requirements than exotic species, and there is considerable variation in needs within each broad group.

Where the aim is the re-establishment of the native community, knowledge of the nutrient budget of the original community will guide in fertilisation. Stability of such a community is unlikely if nutrient inputs exceed that normally present and invasion and proliferation of exotic weeds is likely.

Microbiological Management of Replaced Soil

Microbiological management and its results are almost inseparable from nutritional management. Nutritional regimes affect microbiological functioning, and the presence of certain organisms will greatly affect the nutrition of some plants. Examples are nitrogen fixation by legumes and some non-legumes and increased growth with mycorrhizal infection of plants in low phosphorus situations.

In general if surface soil is replaced without stockpiling, microbiological problems should be minimised. Inoculation with Rhyzobium culture is, however, advisable with all exotic legumes in all soils and with native legumes in mixed, stored or non-surface soils if inoculant is available. Inoculation with mycorrhizal propagules is not as yet widely practiced, but there are indications that commercial inoculants will be available in the future.

Building up of soil organic matter with pasture or mulches should ensure a broad suite of micro-organisms including the organisms responsible for nutrient cycling in the soil.

Fertiliser regimes should be developed in the knowledge of their effects on the microbiological population. Application of nitrogen, for example, suppresses symbiotic nitrogen fixation.

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