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

GUIDELINE

Tailings Impoundment
for Uranium Mines

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INTRODUCTION

1 The Code of Practice on the Management of Radioactive Wastes from the Mining and Milling of Radioactive Ores (1982) requires the use of the best practicable technology to ensure that the release of radioactive material is minimised during all stages of mining operations and after the completion of such operations. In addition, the Code specifies that radioactive wastes shall be managed such that exposure to radiation of employees and members of the public is as low as reasonably achievable, and below the relevant limits prescribed in Schedules 1,2,3 and 4 of the Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (1980).

2 This guideline is aimed at assisting users of the Code in siting, constructing, operating, decommissioning and rehabilitating uranium tailings impoundments. It presents a range of current options for impoundment of tailings from uranium mills. In presenting this material, account has been taken of the various influences which could determine the best practicable technology applicable to a particular site, and of the information required by the appropriate authority in relation to approval for a tailings impoundment system.

3 While the options presented imply a wide range of possible strategies, many will be inappropriate for a specific site. Moreover, it is not intended that the guideline restrict or exclude consideration of innovative alternatives, given that the options in the guideline (and any alternatives) are interpreted in accordance with the Code. In all cases, however, the approval of the appropriate authority is required for all aspects of tailings management and disposal to ensure that the best practicable technology is adopted and the provisions of the Code complied with.

Overview

4 Uranium mill tailings are the solid residues and associated liquids remaining after uranium has been extracted from an ore. The solids consist primarily of the finely ground bulk material of the original ore, and also contain a variety of chemical substances precipitated from the tailings liquids. The tailings solids and liquids contain both radioactive and non-radioactive materials which, if released and dispersed in the environment in unacceptable amounts, may have some detrimental impact on persons and the environment.

5 Uranium mill tailings differ from most other metal mill tailings in their significant content of radioactive components. The physical and chemical properties of the

tailings will have a considerable effect on their structural behaviour and their leachability during the operational phase of the project, as well as during decommissioning and in the long term. These properties in turn depend on the nature of the ore, its hardness and acidity, the dissemination of the ore minerals in the gangue materials and the particular mineral form in which the uranium occurs. These factors will influence the fineness to which the ore is ground before leaching and whether an acidic (e.g. sulphuric acid) or basic (e.g. sodium carbonate) leach is used.

6 With a porous sandstone, the grind may be as coarse as '80% greater than 0.8 millimetres', or when there is considerable shale with the ore, as fine as '75% below 45 micrometres'. The very fine material below 75 micrometres is referred to as "the slimes". Depending on the tailings management system used a high proportion of clay mineral in "the slimes" can lead to tailings which take a long time to dewater and consolidate and therefore to stabilise.

7 During the extraction process 90% to 97% of the uranium is removed leaving essentially all the other radionuclides of the uranium decay chain in the tailings slurry. Some of these radionuclides are in solution in small quantities. The slurry also contains undissolved and dissolved heavy metals in varying proportions plus certain amounts of mill chemicals. In general, most of the radionuclides are concentrated in the finer tailings fraction; as much as 75% of the total activity can be found in the minus 75 micrometre fraction.

8 The tailings from acid leach processes are normally neutralised and then adjusted to pH 8 or higher with lime, to reduce the concentration of soluble heavy metal contaminants. If the ore contains pyrites or other sulphide minerals they will normally be discharged with the tailings. These sulphide minerals, even at low concentrations, can produce sulphuric acid by chemical and bacterial oxidation processes. Acid produced by those processes will initially react with any excess lime, and other basic materials present in the tailings. If the concentration of basic materials is insufficient to react with the acid produced, the pH will continue to decrease and heavy metals may redissolve. Movement of the acidic solutions through the tailings will leach the heavy metals and release them to the environment by seepage. The presence of pyrite or sulphide minerals in the ore and waste rock can thus have a very significant effect on the long-term behaviour of tailings and waste rock piles as potential sources of pollution.

9 Radiological protection problems arise in the long-term management of mill tailings due to the presence of a number of long-lived radionuclides of the U-238 decay chain which remain in the tailings following conventional extraction processes. (These problems will be compounded if there are significant quantities of Th-232, with its decay chain, associated with the uranium orebody.) The radionuclides of most concern are :

Th-230: alpha emitter, 80,000 y half-life,
Ra-226: alpha emitter, 1,600 y half-life, (daughter of Th-230).
Rn-222 plus daughters: alpha and gamma emitters, Rn-222 has a 3.8 day half-life, (continually produced from Th-230 via Ra-226).

There will also be a small percentage of the original uranium remaining in the tailings. For an orebody of, for example 0.3% uranium, a 95% extraction efficiency would leave the tailings with 0.015% uranium. However for a rich orebody of say 3% uranium a similar extraction efficiency would leave 0.15% uranium in the tailings and in this case the tailings would be classified as specified material as defined in the Code.

10 The principal potential modes of radiological impact of these radionuclides are via :

- Dust - which may be inhaled directly or deposited in the nearby environment,

- Water release - particularly Ra-226 (and Th-230) in seepage leading to the contamination of surface and ground waters and thence food chains,

- Radon emanation - leading to lung exposure of people in the vicinity, but also, at very much reduced levels, of those who may be quite remote, and

- Gamma irradiation - arising from the short-lived daughters of Rn-222 and a source of exposure only in the immediate vicinity of the tailings.

11 Although the uranium has been removed from the ore, thereby reducing the quantity of elemental radionuclides, the milling process has increased the potential mobility of the remaining elements (both radioactive and non-radioactive) in the tailings. As such, careful disposal of the tailings is required to limit the transfer of mobile constituents to people and the environment.

12 The basic design and operating objectives for the impoundment of the uranium mill tailings in all cases should be :

- to provide an impoundment which is both physically and chemically stable, and

- to control the loss of radioactive elements to the environment to acceptable levels.

13 The important considerations that influence the effectiveness of tailings impoundment relate to both site selection and choice of the impoundment system. Each potential tailings impoundment site has inherent site-specific advantages and disadvantages. Site selection should make use of the site-specific advantages. The design and engineering should then account for the site-specific disadvantages.

14 Site selection and the design and engineering of the tailings impoundment should be considered in conjunction with the overall design and planning of the mining and milling operation. Processes and methods used in both the mine and mill will have a direct influence on the requirements, performance and cost of the impoundment.

15 The concepts of "storage" and "disposal" should be carefully distinguished when evaluating tailings management systems. The requirement of storage, that is, confinement of wastes over a limited period of time with the possibility for retrieval and eventual disposal of tailings, can be met by any properly sited and designed tailings impoundment. However, tailings disposal is the desired management objective. In this case there is no intent to retrieve and, more importantly, no reliance on continued surveillance and maintenance to ensure integrity of the impoundment system. The time following decommissioning of the mill and rehabilitation of the tailings impoundment after which surveillance can be discontinued may vary considerably with the impoundment design and, in particular, with certain site-specific parameters.

16 There can be no guarantees that in the long term tailings deposited on or near the land surface, regardless of the method used or the site selected, will not be eventually dispersed into the environment. However, the design goal for the impoundment system should be to dispose of tailings using the currently available best practicable technology, so as to minimise the possible future rates of release of radionuclides into the environment and the need for long-term surveillance.

17 Detailed information should be supplied to the appropriate authority on all factors which will influence the effectiveness of a proposed tailings impoundment system, including:

- the characteristics of the orebody, and the processes and treatment to be used in the production and handling of tailings,
- the availability of sites for tailings impoundments and the basis of selection of the recommended site,
- the type of impoundment proposed, the design of the structures and their expected behaviour,
- the type of tailings management to be utilised,
- the long-term rehabilitation proposed for the tailings impoundment, and
- the assessed environmental impact of the impoundment during operations and for the long term.

SELECTION OF IMPOUNDMENT SITE

18 One of the most important aspects to be addressed in tailings management is the selection of a site for the tailings impoundment. The site-selection process consists of collecting appropriate information regarding the natural conditions, geology and geomorphology of the region concerned, and then choosing a site which has a favourable combination of conditions with respect to those factors which govern the rehabilitation strategy to be adopted and long-term integrity of the impoundment. The tailings impoundment site will be within the restricted release zone; approval of the zone is required under clause 5(1) of the Code.

19 The criteria that must be met by the selected site include:

- adequate storage capacity for the total quantity of tailings to be produced,
- away from population centres,
- away from potentially active fault or seismic areas,
- nearby availability of adequate quantities of suitable natural materials required for the construction of the impoundment and eventual cover structures, and
- no extraneous catchment area and not subject to flooding.

20 Desirable site characteristics are :

- low permeability strata in the impoundment area,
- minor consequences of failure,
- foundation properties sufficient to support the tailings and associated structures without high settlements,
- geological formations which will resist chemical (and physical) attack by the tailings liquid,
- strata below the impoundment area which readily absorb radionuclides, and
- that the geological and geomorphological processes known to be operating in the area would improve rather than prejudice continued containment of the tailings.

21 The site selection process cannot be carried through to a final decision without considering, at least conceptually, the impoundment design. The decision relating to final site selection is frequently arrived at concurrently with those pertaining to impoundment design and rehabilitation as discussed in this guideline and the guideline on <u>Decommissioning and Rehabilitation of Uranium Mine, Mill and Waste Disposal Sites</u>.

22 In undertaking an evaluation of potential impoundment sites, the following information should normally be obtained and made available to the appropriate authority:

- <u>Mining Operations</u>
  - characteristics of the orebody, including mineralogy and grade,
  - methods, plans and sequences of mining,
  - rates of production of barren wastes, contaminated wastes and ore, and
  - locations of the proposed impoundment sites relative to the mill site and the mine.
- <u>Milling Processes</u>
  - expected production rate of the tailings,
  - processes and reagents to be used,
  - water requirements, and
  - chemical, physical and radioactive properties of the tailings.
- <u>Site Data</u>
  - topography and current land use,
  - hydrology and current water use (surface and groundwater),
  - geology and surficial soils,
  - regional geomorphology,
  - seismology,
  - meteorology,
  - demography,

- cultural and recreational resources, and

- ecology.

23 An evaluation of information on the topics listed above should lead to the selection of a limited number of the more feasible sites which can then be evaluated in greater detail to select the final intended site. The more detailed evaluation requires compilation of additional information for each site derived from exploration, drilling and testing, geophysical surveys etc., including :

- <u>Geology</u>

  - geological strata and surficial soils in the impoundment area, and their engineering properties,

  - foundation conditions at embankment and structure locations,

  - lateral and vertical distribution and permeability of the strata underlying the impoundment,

  - existence of faults, fractures and joint patterns that may provide preferential seepage channels, and

  - geochemical properties of soil and underlying strata, including their chemical exchange capabilities.

- <u>Hydrogeology</u>

  - depth to water table, including perched water tables if present,

  - magnitude and trends of annual water table fluctuations,

  - distance to nearest points of groundwater, spring water, or surface water usage (includes well and spring inventories),

  - relation to recharge area of groundwater,

  - groundwater quality, and

  - possible chemical effects of pollutants in seepage water along potential flow paths.

24 On the basis of the evaluation studies referred to above, a proposal for the location of the tailings impoundment site should then be submitted to the appropriate authority for approval. Prior to construction, a report should be compiled and submitted to the appropriate authority which details a range of environmental baseline data for the approved site. This data would include:

- the concentration of the radioactive and non-radioactive nuclides in soil, water, air and biota in and around the site which would be expected to be monitored and used as indicators of the integrity of the impoundment and of the impact of the impoundment on the environment;

- the external radiation exposure levels in the region of the site; and

- the radon exhalation rate(s) from the region of the site.

TYPES OF IMPOUNDMENTS

25 Tailings impoundments generally consist of a combination of both natural and man-made features. The types of impoundment systems discussed in this guideline are not exhaustive, and innovative proposals for new facilities are encouraged, provided such proposals are adequately supported when submitted to the appropriate authority. The following types of impoundments considered are:

- Valley dam impoundment,
- Ring dyke impoundment,
- Mine-pit impoundment,
- Specially-dug pit impoundment, and
- Underground mine impoundment.

The appropriate authority should be provided with a detailed assessment of why a certain type of impoundment has been selected and why that type of impoundment is considered the best practicable technology for the site.

Valley Dam Impoundment

26 The confinement basin is formed by constructing an embankment across a valley. The valley forms three sides of the impoundment and only a relatively short dam is generally required. This type of impoundment can therefore be used only in hilly areas with adequate relief to achieve the required storage with an acceptable dam height.

27 The following factors should be considered in assessing the location and use of a valley dam impoundment:

- Valley impoundments are chosen to maximise the use of natural topographical advantages of the area. The shape and locations of the impoundment basin are therefore determined by the availablility of suitable sites within a reasonable distance of the mine. Because the characteristics of the site are fixed by nature there is usually little scope for varying the site locations to avoid unfavourable features.

- Since the site locations are dictated by the available natural features, total distances from the ore bodies to mines, stockpiles, mill plants and impoundments may be substantial. Shorter distances reduce the overall surface area that is affected by the mining and milling operations, with attendant reduced risk of contaminating the environment by spillage.

- Borrow material for the construction of the dam wall should, if suitable, be obtained from within the storage area.

- Rainwater runoff from areas adjacent to the tailings impoundment area should be diverted away from the impoundment. Diversion drains to prevent the contamination of runoff water by the tailings are required. For the long-term protection of the tailings impoundment these drains should be designed to carry the maximum probable flood from their catchment. Ideally, such a tailings impoundment should be located at the head of a natural drainage area, allowing the diversion drains to discharge to an adjacent catchment. If this is not practicable, the diversion drains should be continued downstream of the dam for an adequate distance so that any scour in the areas of steep gradients will not progress back to the dam. Discharge on the contour into natural side water courses is preferred.

- Because of the shape of the valley, tailings depths are shallow along the three natural sides and become progressively deeper towards the middle. The average tailings depth is therefore generally fairly small and the final surface area relatively large. This tends to increase the area of environmental impact, the surface area for seepage and wind erosion, and the volume of the cover required for stabilisation.

- For a given volume of tailings the valley dam will have to be relatively high with a subsequent steep hydraulic gradient at the dam. Spillages and seepages from the dam area will rapidly join the surface drainage system of the area.

- The shape of the valley is often irregular. Complex shapes may render installation of a well-managed tailings facility difficult and costly to operate. Where line discharges are used along the dam embankment, soft slimes zones usually form along the outer basin edges, creating placement difficulties and differential settlement problems for the cap.

- Valleys often occur as a result of some underlying weak geological feature, such as a fault or shear zone, which may also be a zone of higher permeability. Deep alluvium deposits are often asociated with valley floors. The horizontal permeability of such deposits is often high. Deep impermeable cut-offs will then be required with substantial grout curtains through the higher permeability rock to minimise the seepage at the dam area.

- A valley normally restricts seepage to a known seepage path to and along the valley floor towards the dam. Monitoring and measures to return seepage flows to the impoundment during the operational phase are therefore relatively simple.

- Since the valley forms three sides of the impoundment and only a relatively short dam wall is required to complete the impoundment, this type of impoundment is often cost-effective.

Ring Dyke Impoundment

28 Ring dyke impoundments are formed by constructing a single self-closing embankment usually on relatively flat terrain. The head of a small valley is often used with part of the ring dyke following the catchment divides so that the total volume and cost of the required earthworks is minimised. Alternatively, where the terrain is more undulating, the impoundment may be formed by a succession of valley embankments linked by low saddle embankments, constructed in single or multiple stages. However, a variety of shapes may be used, with perimeters ranging from square or rectangular to curved or irregular. Moreover, internal embankments may be used to sub-divide the impoundments into two or more compartments.

29 The following factors and characteristics should be considered in assessing the location and use of a ring dyke impoundment:

- Ring dykes require generally flatter areas than valley dams, and thus there may be greater flexibility in selection of a location close to the mine and mill.

- Close location to the mine may allow use of barren mine waste in the construction of the embankment and the containment may also be used for the disposal of radioactive waste rock.

- Borrow material for the construction of the dam wall should, if suitable, be obtained from within the storage area.

- The impoundment can also be used effectively for storage and evaporation of water if saturated tailings management is used.

- Ring dykes are commonly located near the crest of ridges where the depth to the water table is greatest. This increases the time required for contaminated seepages from the impoundment to reach water courses and allows dilution with uncontaminated groundwater. Also, a greater time period may be available to implement remedial measures where large excursions of contaminated groundwater flow are found to occur.

- The location of impoundments on the crest of ridges exposes the tailings to conditions which favour the evaporation of tailings water. However, such conditions are generally unfavourable for reducing wind erosion of dried-out tailings.

- Ring dykes should be located away from streams and the downstream toes of the embankments should be kept above maximum flood levels.

- A regular shape and minimisation of the catchment area allows good control over the water depth, and the tailings solids build-up, which are necessary for saturated as well as for semi-dry tailings management.

- It is generally advisable that seepages from the impoundment through the dam and the upper foundations be collected and pumped back into the water management system during the operational phase and the construction activities associated with the rehabilitation phase of the project.

- Where the embankment is elevated substantially for its full length above the surrounding natural surface, solutions for the long-term discharge of rain runoff from a rehabilitated ring dyke impoundment are costly.

- High ring dykes, especially when located on ridges, have a significant visual impact.

- The construction of ring dykes requires the use of considerable quantities of earthfill and/or rockfill.

- Additional tailings storage capacity can be readily achieved by constructing additional stages or additional dykes.

Mine-Pit Impoundment

30. Worked-out mine pits may be used for the containment of tailings. The procedure for backfilling the

pit with tailings varies considerably, depending on the climate, the depth to and variability of groundwater, the proximity to streams, the susceptibility of the pit to flooding, the permeability of the wall rocks in the pit, the mining program adopted, whether wet or dry tailings management is practised and the characteristics of the tailings.

31 In arid regions where evaporation considerably exceeds precipitation and the depth to groundwater is great, it may be feasible to backfill the worked-out minepit to above the water table using general back-fill, then to install a liner followed by placement of the tailings in the pit. The risk of damage to the liner due to settlement of the fill should be assessed.

32 Where the groundwater table is close to the surface it is not possible to store tailings in a pit above the groundwater level. If the permeability of the walls is low or if the groundwater is not a resource, it may be acceptable to place the tailings in the bottom of the pit. However, the preferred upper level of the tailings should then be kept below the lowest expected groundwater level and not be located in the range of the active groundwater fluctuation. Where permeable porous areas occur in the pit walls these should be covered by a liner or grouted.

33 In areas where the net evaporation is low or where the inflow of water into the mine-pit cannot be controlled, then the surface of the tailings will remain wet and therefore it may not be practicable to construct an effective cover over the tailings. In such cases, it may only be possible to spigot a soil material over the top of the tailings, even though this may not provide adequate stabilisation and protection.

34 In some cases mine-pit impoundment may be carried out in conjunction with mining in a different area of the pit. The protection required against radon exhalation and the safety of the operation must be considered in detail. The procedures that would be used for backfilling of the mine-pit with tailings are clearly site-specific and must be engineered in accordance with the prevailing conditions.

35 The following factors should be considered in assessing the use and construction of mine-pit impoundments:

- Their use depends to a high degree on the mining program adopted. For example, they may be used where the orebody is to be mined completely before milling operations commence or where there is an existing worked-out mine pit. If the mining and milling phases overlap there would be a need to construct a temporary storage pond for the tailings until the mine pit becomes available.

- For a low waste-rock-to-ore ratio the tailings may be too voluminous to be contained in the pit.

- The greater depth of burial available provides greater assurance of post-operation confinement.

- Visual and air pollution impacts are low.

- Instability of the pit wall may affect the integrity of any liner.

- Where lining of the pit is necessary, flatter excavation of the pit slopes may be required to facilitate liner installation. However, the resultant requirement for a wider pit could then increase the economic and environmental consequences.

- Where a liner is used to retard seepage from the pit it would also retard water drainage into the pit through the walls, leading to possible instability and/or breach of the pit walls. This problem is overcome where tailings are placed above the water table. Liners may also be subject to deformation and rupture due to differential settlement of the tailings.

- A thorough knowledge of the climate, groundwater fluctuations, rock mass structure and permeability, and transmissivity is necessary for a mine-pit impoundment.

- The use of mined-out pits may complicate future mining operations near the pit, particularly for underground mining methods.

- Uranium-enriched ore zones may be unevenly scattered through the generally mineralised region. As planned pit boundaries are frequently defined by mining economics and not necessarily by ore reserves, the tailings may cover potential ore reserves. Re-mining of the area may be rendered difficult, particularly if saturated or wet disposal techniques are used, whereas containments of dry or semi-dry tailings would be more readily re-mined.

Specially-Dug Pit Impoundment

36 Excavation may be undertaken specifically for the purpose of providing below-grade impoundment. The materials excavated to form the pit may be used to form small

surrounding retaining embankments and for any other structures required at the site. With increasing depth of excavation the procedure becomes essentially similar to the mine-pit impoundment. If the top of the tailings reaches above the natural surface the impoundment approaches a ring dyke impoundment condition. The technique is site-specific and its use depends on the geology and climate of the region and on the nature of the mining operation. Various shapes and sizes of pits can be used, ranging from one large pit to a number of trenches.

37 The procedure in siting and constructing such an impoundment consists essentially of :

- selecting a geologically stable site, with favourable soil and strength conditions to permit easy deep excavation;

- making an excavation of sufficient volume to contain the anticipated quantities of tailings;

- forming surrounding embankments, if required for water management purposes, with material excavated from the pit;

- providing liners or clay filled cut-offs to prevent seepage from the pit through any near surface permeable soil layers, or maintaining the water level in the pit below the level of such horizons; and

- constructing other impoundments which may proceed at the same time as, or subsequent to, the initial specially-dug pit. Progressive rehabilitation will minimise the effects of radon exhalation from the tailings and provide experience in rehabilitation techniques during operations.

38 The following factors should be considered in assessing the location and use of specially-dug pit impoundments:

- the pit should be in a location that is convenient to the mill;

- the location should be selected such that favourable topography (hence favourable drainage) exists. Geological and hydrogeological conditions should be such that the impoundment is positioned generally above the water table, over relatively impermeable horizons, and at locations free from erosion or flooding.

- The system involves considerable excavation, and is only practicable in material that is easily excavated.

- If "saturated" or "wet" management is practised, the tailings may be difficult to rehabilitate. Post-operational settlements of the tailings may lead to drainage problems on the cover.

Providing the site is carefully selected and managed, the impoundment should be relatively free from the risk of erosion, flooding or failure.

Underground Mine Impoundment

39 Underground mine impoundment normally involves separation of the coarse fraction of the tailings from the slimes fraction and using the former as backfill within the mine. In current practice, tailings used as backfill are placed in underground mine areas to serve as floors for mining equipment used in the mining operation, as well as for stope fill. The proportion of tailings which may be returned to the mine is a function of the ore mineralogy and milling operation, which determine the proportion of coarse tailings to slimes. It is possible for 50% to 60% of the tailings to be returned to the mine in this manner. The remainder of the tailings must be disposed of in other ways.

40 The following factors should be considered when assessing the use of underground mine impoundment of tailings :

- Stabilisation of the placed tailings requires that they have a high permeability to permit rapid drainage of excess water.

- Excess water should be confined within the overall mine-mill water management system and not released to the environment without treatment.

- A significant fraction of the radium, thorium and other contaminants are contained within the slimes fraction (approximately 75% of the radium stays in the slimes); thus, underground disposal of the coarse fraction of the tailings does not appreciably reduce the total radioactivity in the remaining waste.

- The surface management of the slimes provides a complex problem where they remain essentially as dense liquids and do not consolidate to any appreciable degree.

- The tailings placed underground will contribute to radon and radon daughter levels in the mine. For active mines, this may require additional ventilation, cement stabilisation of backfill and special precautions for handling the excess seepage from the tailings. Conversely, the backfilled tailings reduce the mine volume which may reduce ventilation requirements.

- Possible re-mining at a later date to recover lower grade ore may be complicated by the presence of the backfilled tailings.

DESIGN OF IMPOUNDMENT DAM STRUCTURES

41 Substantial retaining structures may be required for tailings impoundments; for valley dam and ring dyke impoundments these are generally in the form of earth or rock fill dams. Failure of such structures may have major consequences and great care is therefore required in their design and construction. Consequently, methods developed and in general use for the design, construction, operation and maintenance of large water retaining dams, should be applied to tailings dams, and the design of the dam should be under the control of competent engineers experienced in dam design.

42 The objectives for impoundment structures should be to produce a dam that will :

- satisfy all functional requirements,
- ensure integrity under any foreseeable conditions,
- last indefinitely with little or no maintenance, and
- minimise seepage through the structure and its foundations.

43 Safety considerations and good engineering practice demand that the design of any such dam should satisfy the following design criteria :

- The materials used and the construction of the dam must provide sufficient strength along any potential surface of sliding within the dam and/or foundations to ensure that excessive deformation or actual sliding can never occur. This condition must be satisfied for any possible combination of water and tailings loads, dead loads, imposed live loads and earthquake loads with proper account taken of the effects of internal pore pressures and their effect on shear resistance.
- The dam and its foundations must be able to withstand internal damage (piping) by seepage. This requires that the materials used should be capable of stopping transport through them of any finer materials from an adjacent, less pervious zone, upstream.
- The impoundment should be operated, so that at any time it provides sufficient storage-volume below the crest of the dam to contain the estimated inflow to the system resulting from an extreme rainfall event (probable maximum precipitation) and, in addition, provides adequate freeboard against overtopping by wind-generated waves.

- Adequate slope protection should be provided on the dam against wave action, erosion by wind and water, and weathering.

44 Extensive site investigation and testing of materials will generally be required to determine the suitability and properties of the foundations and of the materials to be used for the construction of the dam. Such investigations should be carried out under the control of experienced geotechnical engineers and geologists, and the findings detailed in a comprehensive form in the design report submitted to the appropriate authority. These investigations involve :

- regional and detailed aerial geological photo-interpretation,
- surface mapping of rock exposures in the impoundment area,
- geophysical surveys,
- detailed geological mapping of the impoundment area and its immediate environs (using information from boreholes, permeability testing, costeans, etc.),
- test pits, and
- laboratory testing of foundation and embankment materials.

45 A design report, prepared by engineers experienced in the design and operation of impoundments, on the proposed tailings impoundment should be submitted to the appropriate authority detailing :

- the intended operation of the impoundment,
- the expected properties of the tailings,
- foundation conditions,
- availability of construction materials,
- geotechnical design parameters,
- embankment design,
- estimated seepage flow-rates from various parts of the impoundment (e.g. through the embankment, the upper parts and the deeper parts of the dam foundation) and a prediction of the seepage loss (including contaminant load) during all stages of and after cessation of the operation.

- construction factors, and

- proposals for monitoring and surveillance.

46 For the embankment stability analyses, conservative values of the shear strength and density of the compacted embankment materials must be used with conservative estimates of the pore pressures within the embankment for all loading cases considered. For potential failure surfaces the minimum factors of safety, that is, the ratio of $\frac{\text{(total shear resistance)}}{\text{(total force contributing to sliding)}}$ along the failure surface, should be as follows :

Loading Condition	Minimum Factor of Safety
End of construction	1.3
Partial pool with steady seepage	1.5
Maximum pool with steady seepage	1.5
Earthquake (in combination with above conditions)	1.0

The magnitude of earthquake loading should be determined from the probable maximum earthquake acceleration for the site area, together with liquefaction of the tailings if this is considered possible.

47 If the foundations under the embankment consist of layers of varying thickness of compressible soils or soft rock or if the bedrock is very irregular, differential settlements would occur resulting in cracks in the dam; in which case the dam should be designed to absorb the anticipated differential settlements. If settlements are expected to be large, the dam should be built higher to allow for these settlements.

Seepage Management

A basic performance criteria of the impoundment is minimisation of the loss of radioactive and non-radioactive nuclides by seepage. The site of the impoundment and the design of the dam structure are the two components which together ensure that seepage is minimised throughout the mining and milling operation and after its cessation. Generally, the most important step is the choice of the impoundment site. An ideal site would have low-permeability strata under the floor of the impoundment

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coupled with the ready availablility of low-permeability soils for the construction of impervious zones in the embankments. Alternatively, such a site could also feature a long seepage path to the point of discharge into the environment. Where the ideal site is not available, the question arises as to the best practicable technology to be applied to and complement the inherent advantages of the impoundment site. A range of technologies is discussed in the following paragraphs.

49 Liners - If natural low-permeability strata are not present, a blanket of low-permeability material (liner) should be constructed to control the seepage from the impoundment. If clay soils or soft weathered rocks are available, this material can be spread and compacted in suitable layers to form a blanket of low permeability; such natural liners should generally have preference over any type of synthetic liner. Liners may be restricted to parts of the impoundment basin to seal potential seepage paths due to the existence of faults, shear zones, porous rocks, sands, or gravels. Clay liners not only reduce seepage flows from the basin but also, as a result of their cation exchange, adsorption and neutralising capacities, serve to retain or at least retard the migration of radionuclides, as well as some of the non-radioactive contaminants. Clay liners from site-derived clays or from imported materials (e.g. bentonite) can be constructed to permeabilities of 10^{-6} to 10^{-7} cm/sec or lower.

50 Long-term retention of these low-permeability characteristics may be affected by a high cation content and by a low pH seepage, but it is accepted that such a liner will not entirely disintegrate. Clay liners are generally constructed in a number of layers, each approximately 200 mm thick, to a total thickness of around 1 metre. Surface cracking occurs readily when drying out is allowed to occur. Such cracking can often be prevented by spreading a 300 mm thick layer of loose soil over the finished compacted surface.

51 Synthetic membranes of plastics or elastomers (0.5 to 1.5 mm thick) may be useful liners for the short term e.g. during the operational life of the mine. However, their long-term stability over thousands of years when subjected to the chemical and physical environment of the tailings impoundment is, to say the least, questionable. The same uncertainty applies to other types of liner materials in common use in water-retaining structures. For example, concrete, asphalt, etc., which may be very effectively used for short-term purposes as temporary liners in tailings impoundments, for storage of sludges and contaminated water, should not be considered as providing adequate long-term seals when disposing of uranium mill

tailings.

52 Grouting - Jointing, shearing and faulting may increase the permeability of rock strata. Cement grouting is generally used under the core of water-retaining dams, down to less permeable strata, in an attempt to seal the seepage pathways from the impoundment. Sulphate resistant grout should be used, where the seepage is high in sulphates e.g. Type D cement or a mixture of cement and ground blast furnace slag. Though grouting is recognised as an effective way of sealing open-jointed rock, the permeability in the narrow band of grouted rock can only be reduced to around 10^{-5} cm/sec. Its long-term effectiveness is also doubtful, especially where the pH of seepage water is expected to gradually reduce after rehabilitation.

53 Placement - If the tailings are deposited to ensure an even distribution of the coarse and fine fractions in continuous layers, after consolidation seepage from the overlying water will be restricted.

54 Seepage Collection Measures - For dams with the highest operating level more than 3 metres above the adjacent natural surface, the impoundment design should incorporate a seepage collection system whereby the collected seepages would be returned to the water management system. In this situation and others where seepage flows from an impoundment are collected during the operational period, care should be taken in the design of the impoundment system to prevent the formation of contaminated springs after the rehabilitation is completed due to the concentration of such seepage flows.

55 Although mainly effective during the operational period a number of seepage collection measures include:

- Seepage collection in a toe drain downstream of the embankment. Seepages through the embankment and through the near surface zone of the dam foundation are collected and pumped back into the impoundment.

- Underdrainage on the floor of the impoundment and pumping back of the collected seepages. This can consist of either a continuous blanket of pervious material, such as sand, or of a system of interconnected pipe drains surrounded by pervious filter materials. Such underdrainage can be located above the impervious strata in conjunction with semi-dry tailings management or under a constructed liner. These underdrainage systems have advantages in that they can de-water the tailings, thereby reducing the total water available for seepage and the pore water pressures in the tailings, with consequent rapid consolidation and stabilisation of the tailings. However, underdrainage systems are liable to clog up by the movement into the system of fine particles from adjacent material, by chemical precipitation and bacterial activity. Special precautions may be required when the tailings contain a high percentage of pyrites.

56 <u>Hydraulic Barriers</u> - These include the construction of water storages or evaporation ponds contiguous to the tailings impoundment.

57 <u>The Long Term</u> - Seepage minimisation during the operation phase is dependent on both active and passive systems. Following decommissioning and rehabilitation of the impoundment most of the active measures are discontinued; subsequently, in the long term, reliance on any active system is undesirable. Accordingly, the impoundment design should incorporate estimates of the seepage rates for the long term and an assessment of the impact of such seepage on the environment.

CONSTRUCTION AND MONITORING OF IMPOUNDMENTS

58 The construction of the impoundment should be undertaken in accordance with the approved design and the use of good engineering practice. Quality assurance programs should be implemented so as to ensure that best practicable technology is achieved. Following commissioning of the impoundment monitoring programs approved by the appropriate authority, should be implemented to assess performance of the structures.

Quality Control during Construction

59 Quality assurance programs should take into account the dam construction materials being used, foundation conditions being encountered, and the methods and scheduling of dam construction. Safety factors determined at the design stage are based on the physical properties of the anticipated construction materials and the anticipated foundation conditions. If, during construction of the impoundment structures, the foundation conditions and the physical properties of the construction materials are found to differ from the assumptions made in formulating the specifications then changes to the specifications may be required to ensure compliance with the principles of the design. Such changes to the specifications should be approved by the appropriate authority.

60 The construction of impoundment structures should be approved at key stages by the appropriate authority to ensure compliance both with the specifications and with the principles embodied within the approved design. To facilitate decision making a comitttee consisting of technical experts should be established comprising representatives from the mining company, the appropriate authority and their respective tehnical consultants. The committee should consider the key stage decisions, including the review of results of quality control testing and of inspections and make recommendations, as appropriate, to the mining company and the appropriate authority.

61 To ensure that the construction of the impoundment structures conforms with the design specifications the mining company should, as directed by the appropriate authority, demonstrate that the materials being used comply with and are placed in accordance with the specifications. This would be achieved by utilising supervising staff experienced in the construction of water management and having the materials tested in accordance with appropriate Australian standards by testing laboratories which are appropriately registered by the National Association of Testing Authorities (NATA).

Monitoring of Impoundments

62 Monitoring, during and after construction, of the structures is undertaken with the objectives of:

- determining the actual performance of the facility, specifically to determine the integrity of the structure and the available safety factors,
- determining compliance with approved objectives, and
- determining the validity of the models being used to predict the future performance of the facility and the adequacy of the rehabilitation measures proposed.

63 Accordingly, the design and construction of the impoundment should include provision for monitoring devices which enable assessments of the stability, settlements, erosion and seepage associated with those structures to be carried out. These assessments form part of the overall monitoring program approved by the appropriate authority.

64 The monitoring program should include monitoring for the existence and extent of seepage from the impoundment. This would include the establishment of a network of monitoring wells and devices around and near the impoundment. (The location and depths of the wells and the parameters to be monitored should be determined in consultation with the appropriate authority.) The information thus obtained will allow the effectiveness of the seepage control measures to be evaluated, the need for remedial actions quickly determined, and the appropriate actions implemented promptly and effectively.

65 The manager should compile, and make available as required by the appropriate authority, a record of data obtained from the monitoring program including:

- observations on the conditions of impoundment structures,
- settlements and other movements,
- details of any repairs carried out,
- water levels in piezometers and wells,
- quality of water from piezometers and wells,
- findings of resistivity and other geophysical surveys,

- quality and quantity of waters collected from seepage collectors,

- dry densities of the tailings at various depths, and

- depths of tailings.

66 The manager should ensure that, during the operational, decommissioning and rehabilitation phases of the mining and milling operation, periodic surveillance inspections are carried out in conjuction with the appropriate authority. The personnel undertaking these inspections should include an engineer experienced in modern dam technology and hydrology and a suitably qualified hydrogeologist. The inspections should be undertaken at least annually or more frequently, as required by the appropriate authority. From these inspections and other assessments, the manager should, where required, propose for approval by the appropriate authority, any remedial work considered necessary to ensure the integrity of the impoundment structure is maintained within the approved objectives.

TAILINGS MANAGEMENT

67 Tailings management includes methods used to place the tailings in the impoundment area and the conditions under which such placement occurs. Tailings management is closely related to water management for the mine and mill since the volume of excess water stored in the tailings impoundment influences decisions regarding the recirculation of tailings water back to the mill, which in turn influences other aspects of the water management system.

68 Selection of the type of system for tailings management is very site-specific. For example, in arid regions systems which allow the tailings surface to dry out, the resultant radon exhalation and wind erosion of particles may, if not controlled, distribute contaminants to the environment beyond the limits of the impoundment. In wet climates sufficient excess water will usually be available to ensure that a water cover of required minimum depth can be maintained at all times. This cover will reduce radon and particulate dispersion but will provide a steeper hydraulic gradient for loss of solutions by seepage to the groundwater system. Nevertheless, it is generally desirable to maintain a water cover or a high moisture content in the tailings.

Comparison of Systems

69 The appropriate authority should be provided with a report comparing the use of various tailings management systems for the project, and why it is considered that the selected tailings management system is considered to be the best practicable technology for the site and the mining/milling operation.

Design Features

70 Tailings management systems should be designed to include the following features :

- Control of distribution of tailings within the impoundment system - Where distribution is effected beneath the water surface by discharge from a floating movable point (barge), considerable control can be exercised on the location and distribution of both the coarse and fine fractions. Where distribution is from the sides of the embankment, control can be exercised over the location and geometry of the beach, and the location and size of the pond.

- Control of excess water volume in the impoundment during the mill operating period - Where a water cover is maintained over the tailings, this water adds significantly to the hydraulic gradient and hence to the potential seepage losses. After rehabilitation of tailings impoundments, ponded water will no longer exist and the hydraulic gradient may be reduced considerably, as will the rate of seepage from the system.

- Control of freeboard in the impoundment - Provision should be made in the water management system to provide for control of the water level in the impoundment, so that the freeboard on the embankment will not be reduced to a level critical to the safety of the embankment. Recirculation of water to the mill, transfer to retention or controlled evaporation ponds, or release of water in accordance with approved standards, are options available for this control. The introduction of water into the restricted release zone should be kept to the minimum level appropriate to the needs of the milling process, so as to prevent unnecessary accumulation of contaminated water.

- Control of density, compressibility, permeability and shear strength of the tailings within various impoundment zones - Where tailings are discharged below the water surface from a pipeline attached to a barge, it is possible to ensure that the fine and coarse fractions are intermixed, thereby developing a deposit which is of uniform permeability and compressibility. Where tailings are discharged from a point source on the beach, segregation of the fine and coarse fractions occurs. This segregation may result in relatively dense permeable deposits in the discharge area, and highly compressible deposits of low permeability slimes away from this area. Segregation of the slimes and coarse fractions into separate areas may render the task of tailings stabilisation and rehabilitation more difficult.

71 Important variations in tailings management systems depend on the moisture content and the physical state of the tailings emplaced, and the method of tailings placement. These are discussed in the following sub-sections.

Saturated Tailings Management

72 'Saturated management' is used here to indicate placement methods by which the tailings are transported, distributed and maintained in a saturated state during the operational life of the project. With this method the tailings are pumped as a slurry from the mill to the impoundment and discharged into a water cover from a floating pipeline. The end of the pipeline is moved

regularly by winch ropes so that the tailings solids are deposited in horizontal layers with minimum segregation. This method of management can result in an even distribution of the coarse and fine fractions throughout the deposit and develop a low-permeability deposit which significantly restricts seepage. During these operations a water cover is maintained over all of the tailings surface, thus eliminating wind dusting and restricting radon emissions.

73 Though only a small depth of water is required over the tailings to prevent wind erosion and reduce radon emission to an acceptable level, a depth of around 2 metres is generally required for efficient discharge. As depths greater than 2 metres can generally be accommodated, the tailings impoundment for saturated water management can be used as the major contaminated water storage and evaporation pond on the project site. This will reduce the area required for water management ponds and the cost of their construction and operation.

74 The large water-storage over the tailings reduces the necessity of other site water-storages. Tailings water can be recycled as process water in the plant for up to approximately 60% of the total plant requirement. However, the free water over the tailings makes large volumes of water available for seepage and enhances seepage due to the increased hydraulic head.

75 Saturated tailings management is more suitable for wet climates, where excess water in the water management system will generally occur, than for dry climates, where excess water is less likely to occur and a large evaporation surface is not required. During decommissioning the water cover is removed to a storage pond of contaminated water or to a treatment plant for eventual discharge from the site by evaporation or release, within approved standards. The tailings surface is then allowed to dry out so that access is possible for the construction of a cover. During the drying out period radon emissions and wind dusting will become of increasing concern. The tailings will be "normally consolidated" and the underwater dry densities of the tailings will be low. The dry densities obtained will greatly depend on the type of material, particle shape, and the percentage of fines in the tailings.

76 When these tailings dry out and are surcharged with a cover structure, large settlements can occur. The cover must accommodate these settlements without loss of integrity. These subsidences, small along the edges and largest over the deepest area of the impoundment, will change the drainage profile of the cover structure. A careful assessment will have to be made of the total long-term settlements which may occur, so that adequate allowance can be made in the constructed drainage surface and future

ponding kept to a minimum. In valley dams with the greater range of tailings depths, large settlement differentials will occur. Also, the often irregular shapes of valleys may make it difficult to discharge the tailings at all locations. In such inaccessible areas, slimes will predominate and may be very difficult to cover.

77 High water-content and low dry-tailings density makes liquefaction of the tailings mass possible e.g. during earthquakes. A well-designed dam can cope with such a condition. After rehabilitation the liquefaction potential will gradually disappear as tailings dry out and consolidate. In localities with regular rainfall it may be very difficult to obtain a dried-out tailings surface to allow access for equipment required for the construction of the tailings cover.

Wet Tailings Management

78 The term 'wet management' is used here to indicate placement methods resulting in tailings that have substantial saturated zones, even though the total tailings impoundment is not saturated throughout the operational life of the project.

79 The method covers the discharge of a tailings slurry onto a beach above the water table. This is a conventional management method in which the coarser particles settle out close to the discharge point as the tailings flow over the beach. Excess water and slimes are collected in a pond at the end of the beach. The slimes then settle and the partially clarified surface water evaporates or is decanted and recycled to the plant as process water, or to other ponds for storage or evaporation.

80 Using a variable location single point or line discharge allows some control over the size and location of the pond and beach. If the tailings dam is also used for water storage, the pond may be large.

81 Underdrainage systems are not usually provided as part of this management method. The area below the pond surface elevation remains wet and saturated and has low shear strength. For this reason, discharge in the vicinity of the dam wall is common. If large beach areas are maintained to limit pond size and water pressure heads to reduce seepage, the beaches may dry out and be subject to wind erosion. Only a limited capability exists for keeping beaches wet by additional discharges from the discharge points. The pond and soft slurries are located adjacent to the basin sides remote from the discharge. Large areas of soft, permanently wet slimes result, and these may be difficult to effectively cover using mechanical equipment at the time of tailings pile stabilisation. As the pond

elevation rises and water is distributed over new areas, seepage losses can increase. With the comparatively large size of the pond, which is typical for this system, large areas of the dam are wet and saturated for long time periods.

82 When the tailings deposit is ready for stabilisation the major portion is saturated. The deposit consists of incompletely consolidated tailings with a high water table, and it has large zones of under-consolidated slimes with very low strength. The slimes may have void volumes greater than the volumes of the solids. The high water table provides high pressure heads that tend to induce seepage.

83 Significant excess pore pressures can exist in the slimes creating unstable conditions under imposed loading. The excess pressure head is dependent on the permeability (which is dependent on other factors, e.g. the grain size of the material in which it occurs). The time required for dissipation of this excess pressure head after shut-down of the mill will range from nearly zero for the very coarse beach area to hundreds of years for the very fine slime zones. In time, the excess pore pressure will dissipate, resulting in an effective stress increase within the tailings deposit. Similarly, as the water table in the impoundment slowly reduces to the base of the dam, the effective stresses in all the tailings increase. These stress increases can be large and result in large subsidence. Lesser subsidence occurs in the zone with coarser-grained tailings. The large differences in settling rates and amounts in the various areas of the tailings piles can be anticipated to damage the integrity of a cap and change a contoured drainage pattern on the impoundment.

84 The main characteristics of a wet disposal system are :

- high water table and pressure heads, hence high seepage gradients at the liners;
- large volumes of contaminated water available for loss by seepage;
- appreciable areas of soft slimes with low shear strength that are difficult to cover;
- high tailings compressiblity combined with high effective stress changes, resulting in high surface settling and differential settling;
- high water content and low tailings density ensures a liquefaction potential for the tailings mass, thus increasing the risk and consequence of dam failure; and

- lower operating costs and the need for a single tailings and water impoundment.

Semi-Dry Tailings Management

85 The term 'semi-dry' refers to a method of tailings placement which relies on a rapid systematic reduction, by evaporation and bleeding, of the water content in a relatively thin layer of newly placed tailings. The consequential consolidation ensures that the body of the tailings generally consists of over-consolidated tailings with a relatively high shear strength. Development is continuing on a number of methods which have been used to obtain this condition.

86 Generally, tailings from the mill are first thickened to a solids content which still allows efficient transport by pipeline. The solids content can vary from below 40%, to 50% and over, depending on the tailings properties, such as their particle gradings and shapes. The thickened tailings are placed for a short depositional period, so that they are distributed in a layer of equal thickness, over a selected area of suitable slope. When placement in that area ceases, the solids settle out and some of the water bleeds to the top and runs down the slope where it is collected and transferred to a water storage pond. Some of the water may also be absorbed into the underlying unsaturated tailings. Evaporation is allowed to remove further water from the fresh tailings layer until an unsaturated, consolidated (semi-dry) layer of tailings is obtained.

87 An underdrainage system is required under the tailings disposal site to collect and remove any seepage water moving down through the tailings. Bleed water from the tailings and rainfall runoff are collected and placed in separate water storage ponds for re-use in the mill process, for evaporation, or directed through a treatment plant for discharge from the site.

88 Evaporation of water from the thin layer of tailings is controlled so the tailings are no longer saturated but are at negative pore pressures which induce effective stresses with attendant consolidation. Moisture contents of around 85% saturation should achieve this objective while still minimising the dispersion of radon and the tendency to desiccate the surface to dust. Increasing desiccation allows wind erosion to occur; to prevent this, fresh tailings are placed over the previous layer. It should be noted however that the fines tend to be concentrated near the upper surface of each successive layer and on drying tend to form a slightly cohesive delicate crust. This crust resists wind erosion until damaged and is

renewed with each successive layer. Where dusting does occur, beaches can be dampened by discharging water or more tailings, or by applying a chemical crusting agent.

89 This method of tailings management allows cover construction to be carried out immediately after milling ceases, with good stable drainage grades promoting runoff without erosion. Two techniques to achieve effective semi-dry tailings management are :

- Coning, where the thickened tailings are discharged from an elevated position near the centre of the impoundment area :

  - The tailings solids settle out on a gradually decreasing slope to form a cone. The excess water evaporates or runs down the slope to a peripheral catch drain at the toe of the cone, from where it is directed to a storage pond. Experience has shown that normally more than 95 percent of all solids including those of sub-micron sizes remain within the sloping deposit. Rain runoff from the tailings surface only erodes a small fraction of the tailings fines which then can settle out in the storage pond. The surface of the tailings area is wetted continuously by new slurry, so wind dusting and radon emission are reduced. Resultant slopes are of 5% to 8% depending on such factors as the grading of the tailings, the percentage solids of the thickened tailings, the temperature of the tailings, pH, and climatic conditions at the site.

- Sub-aerial tailings deposition, where a thickened tailings slurry is discharged sequentially onto sections of a tailings beach from multiple points to form a layer of approximately 100 mm thickness:

  - The discharge is moved to a new section of beach when this thickness is obtained, while the solids in the first section are allowed to settle out and excess water evaporates or drains off to the bottom of the sloping tailings surface, from where it is collected and recovered. The slope of the beach is approximately 1%. A considerable proportion of the slimes in the tailings concentrates in the top of the settled tailings layer. Successive layers of tailings form a highly stratified deposit with moderate permeability parallel to the layer interfaces and low permeability normal to the layers. This low vertical permeability through the top of each layer prevents the entry of substantial quantities of water during the placing of later slurry layers and results in a partly saturated deposit. Layers are allowed to dry to around 85% saturation before the next layer is placed. The dried-out slimes form a sealing layer which affords some protection against wind dusting and is believed to reduce radon emissions. The depositional sequence and permissible rate of rise depends on the climatic conditions of the site.

- A good underdrainage system is required to ensure that a gradual increase of the saturation level in the lower levels of the deposit does not occur. Well-controlled and specific tailings depositional techniques are required to prevent underdrainage clogging and binding. An effective system to rapidly remove bleed water from the tailings and rainfall runoff from the tailings surface has to be incorporated into this system. Seepage of contaminated water into the underlying ground will be small compared with that which occurs from semi-wet and saturated tailings management structures. Structures to contain the tailings may not have to be designed as water retaining structures. Long-term settlements of the tailings mass will be small. Long-term seepages from the impoundment will depend on the effectiveness of the cover structure in preventing the percolation of rainwater into the tailings.

- During sun-drying of the beach areas, negative pore water pressures are induced that produce high effective stresses in these beach areas of tailings. These stresses tend to consolidate and reduce the tailings void ratio. In this manner changes in void ratio, i.e. from greater than 1.5 to less than 0.8 are effected. The lower void ratio implies :

  . lower moisture content at saturation,

  . considerably lower settlement potential under increases in effective stress,

  . lower total tailings volume,

  . considerably increased shear strength, and

  . low liquefaction potential.

Dry Tailings Management

90 This management technique involves the drying of tailings to a moisture content that will permit transport into an impoundment other than as a slurry. Transport can be by conventional earth-moving equipment or by conveyors. Heap leach waste can be considered as dry tailings.

91 Dry tailings can be produced by evaporative drying in layers which can then be transported to the eventual tailings impoundment. Tailings "drying" by belt filtration in the milling process is currently receiving considerable attention. Tailings resulting from this process generally still have a moisture content above the liquid limit and are difficult to handle without some further reduction of the moisture content. Some mills currently using belt filtration revert to a form of wet tailings management by rewetting the tailings to a thick slurry so that it can be pumped into the impoundment.

92 Dry tailings with a moisture content below the liquid limit can be trucked, spread and compacted as normal earthfill to a suitable shape for subsequent cover by suitable barren materials. Tailings with a moisture content just above the liquid limit can be spread from conveyors in trenches for subsequent cover when moisture reduction by evaporation occurs in the upper layers.

93 Cover construction should be progressive with a minimal surface of tailings exposed to the elements at any time, so that drying out with the potential for wind erosion and erosion by rainwater runoff does not become a problem.

REHABILITATION OF TAILINGS IMPOUNDMENTS

94 After the active operation of the mill plant and its associated tailings impoundment ceases, a program must be carried out to contain the tailings for the indefinite future so as to meet the requirements of health, safety and environmental protection. A protective cover placed over the tailings impoundment is usually necessary to protect the tailings from natural erosion forces and to restore the area to a suitable land-use capability. The protective cover must also serve the important functions of controlling the exhalation of radon gas and the emission of gamma radiation to acceptable levels.

95 An engineered cover, to a standard meeting both the "disposal" and "rehabilitation" requirements has yet to be constructed in Australia and few examples, if any, exist elsewhere in the world. It can be expected that presently held ideas on cover requirements and on best practicable technology for rehabilitation will be subject to change. The following comments therefore should not be regarded as definitive but as a guide to the present state of the art concerning rehabilitation structures. The guideline on Decommissioning and Rehabilitation of Uranium Mine, Mill and Waste Disposal Sites should also be consulted.

96 Prior to commencement of any mining operations, a detailed proposal outlining measures for rehabilitation of the tailings impoundments should be submitted to the appropriate authority for approval. A program of monitoring and testing of the tailings during milling operations to obtain data required for the final design of the rehabilitation measures proposed is also to be provided to that authority.

97 Prior to commencement of rehabilitation work for a tailings impoundment, or when directed by the appropriate authority, a proposal should be submitted to the appropriate authority for approval, giving full details of the rehabilitation measures to be taken.

98 A number of requirements are currently recognised as necessary for an acceptable tailings cover they are detailed below:

- The cover placed on the tailings should remain effective over a very long time span to prevent the exposure of tailings to erosion by wind and water. It is not practicable at present to determine a definite life for a cover, as the future effects of wind and water erosion on the cover cannot be accurately assessed. For example, if local exposures of tailings occur, e.g. by gullying, a rapid dispersal of all tailings into the surrounding area may not necessarily occur. Furthermore, by the time a well-constructed impoundment cover loses its effectiveness, the level of contamination potential of the tailings may have decreased.

- The radon exhalation and gamma emission from the tailings impoundments should be reduced by the cover structure to acceptable levels. These levels should be such that the exposure to radiation of members of the public is as low as reasonably achievable and below the relevant limits prescribed in Schedules 2 and 4 of the Radiation Protection (Mining and Milling) Code 1980. Furthermore, the appropriate authority may require that the radon exhalation from the covered tailings should be limited to a rate consistent with future land uses and pre-operational background levels. As an example the radon flux from uncovered tailings was reduced by a factor of over 100 from 8 Bq $m^{-2}s^{-1}$ to 0.07 Bq $m^{-2}s^{-1}$ by the use of a cover consisting of 610mm clay, 1810mm overburden and 300mm topsoil

- The seepage through the tailings should be minimised so that dispersal of contaminants by groundwater remains at a low rate. As all rainwater which percolates through the cover into the tailings will ultimately be discharged out of the tailings, the cover should be designed to prevent rainwater percolation as far as is practicable.

- Where the climate allows, a self-sustaining vegetation should be established on the cover. Not only will this assist in blending the impoundment into the landscape but also greatly reduce the erosion due to wind and water, and reduce, by transpiration, the water available for percolation through the cover.

99 To satisfy the above requirements the thickness of the tailings cover structure may have to exceed 3 metres. A combination of cover materials usually provides a better protection than any one material used alone and a number of zones and layers of natural soils and rock are generally used to form a complete impoundment cover. The material selected for these zones will greatly depend on the economic availability of suitable materials at or near the site, on the climate of the area, on the type of impoundment used, and on the tailings management system employed for placing the tailings in the impoundment.

100 Zones of the cover structures may consist of layers of clay soil, rock, soil and rock, and topsoil and

vegetation. These zones are discussed in the following paragraphs.

101 Clay soil - This material is selected for its low permeability property when compacted. A clay soil zone will minimise the infiltration of rainwater into the tailings. Such a zone is also effective in substantially reducing the radon exhalation, especially when the zone retains a high moisture content. To maximise its effectiveness it should be placed in layers of approximately 200mm thickness and compacted under moisture control to a design density of not less than 95% standard dry density. The total thickness of such a clay zone may be expected to range upwards from 0.6m. If an adequate quantity of low-permeability clay soil is not obtainable from near the site, the permeability of other soils can be reduced by mixing with bentonite or using other admixtures.

102 This is the main protective zone of the cover. Other cover zones are provided mainly as a physical protection of the clay zone, to keep the clay zone moist (which prevents cracking and minimises radon diffusion), to reduce root penetration and animal burrowing and to increase the range of potential land uses of the impoundment area. A 1 metre zone of moist clay will usually be more than sufficient to comply with the radon exhalation requirements and such a zone together with other protective zones will effectively reduce the gamma radiation to the pre-operational baseline level.

103 Rock - This may consist of barren waste rock from the mine or of specially quarried rock or gravels. The material should be resistant to weathering so that it retains its properties over a long time. Such rock may be resistant to wind and water erosion but ineffective in reducing radon exhalation. When used at the surface, rock will tend to collect wind-blown soil particles which may form a favourable habitat for vegetation growth between the rocks. Rock will resist invasion of burrowing animals, for example, rabbits and wombats.

104 An important use of rock is as a pore breaking zone, preventing the capillary rise of contaminated tailings water to the upper cover layers, where it can interfere with plant growth and be dispersed to the environment by wind and rainwater. Where such a pore breaking zone is overlain by soil with small particle sizes; a filter should be constructed between the zones to prevent movement of fine particles into the pore breaking zone. Such movement would gradually render the pore breaking zone ineffective as well as destroying the integrity of the overlaying zone.

105 Soil and rock - Mixtures of soil and rock can be effectively used to improve the properties of each

material. Such a zone will be more resistant to erosion than soil alone, will have a low permeability compared with rock alone and will be able to sustain vegetation. It will also be effective in reducing radon exhalation if suitably compacted and kept moist.

106 Topsoil and vegetation - Topsoil generally forms the upper layer of the cover structure, and should be specially selected for the establishment of a self-sustaining vegetation cover. The choice of particular plant species must take account of their adaptability to the particular conditions in the area of the impoundment site such as climate and the water retention capacity of the cover. The topsoil should overlie a soil or soil and rock zone which can store adequate water to sustain the vegetation through dry weather periods.

107 In nature, a soil profile overlaying rock usually shows a gradually reducing permeability with depth. Where zoning is used contrary to such a profile, the tendency will be for fines from the higher areas to migrate into the more open structures of the lower zones. Changes will also occur to the level of soluble contaminants held in the upper tailings layers and the need for a pore breaking zone may by then have disappeared.

108 Pipe drains may be used to collect and discharge rainwater which seeps through one or more of the cover zones. Whilst it is doubtful if these pipes will remain effective in the long term, they may be very useful for short-term purposes.

109 In the longterm at most locations, the upper surfaces of the cover will gradually erode so that lower zones become exposed and have to take over some of the functions of the eroded zones, such as the maintenance of the vegetation cover.

110 The main protection zone, the low-permeability clay soil zone, is therefore best located as close to the tailings as practicable. Where tailings below the cover can be expected to be saturated frequently, where high osmotic pressures can be expected in the tailings, and probably also for tailings with a high pyrite content, a pore breaking zone should be placed between the clay soil zone and the tailings. Where saturated or wet tailings management was used it may be advisable to use a pore breaking zone as a first zone over the tailings, to allow for temporary upward movement of tailings water.

111 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, due 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 3.0%.

112 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 is indicated. Such spillways are preferrably located over lower sections of the outer embankment as wide structures of uniformly graded rock fill, allowing the normal discharge of runoff water to flow through the rock fill so that the flow velocities are kept small.

113 In very dry areas it may be practical to shape the surface of a ring dyke impoundment to an internal drainage system with drainage grades from the outer edges to the centre. After infrequent heavy rain storms a temporary pond may be formed, from where most of the collected surface water can evaporate. In such a case, an emergency spillway at the location of the lowest embankment height should still be provided. If the climate is so dry that it is unlikely that any cover vegetation can be sustained, a zone of gravel or broken rock over a low-permeability clay soil zone may give a good protection. Where some vegetation can be expected a soil/rock upper zone would be better than rock alone.

114 Zoning for a cover structure is greatly dependent on site conditions such as economic availability of materials, total climate, vegetation requirements and limits, type of tailings management used, and moisture content in upper tailings. Figure 1 shows some zoning variations corresponding to different rainfall and tailings conditions.

115 Figure 2 shows a rehabilitation option for an open mine pit tailings impoundment. In this case, below ore grade uranium material, wastes from plant and water management structures and all waste rock can also be placed in the pit resulting in a small hill covering all the project wastes in one location. Where saturated or wet tailings management in a pit was used the future settlements could be quite large. The constructed shape of the impermeable compacted clay soil layer should allow for these settlements to occur without the formation of areas of

negative curvature where seepage rainwater could be ponded, resulting in unnecessary seepages into the pit area as well as the probability of crack formation in the clay soil.

116 Figure 3 shows a possible rehabilitation system for a below grade excavated tailings pit. For this example, it has been assumed that saturated tailings management was used with water storage over the tailings in an area with high evaporation, so that the upper layer of tailings could be effectively dried out before the clay soil layer is constructed.

117 Figure 4 shows a trench tailings disposal system which is one type of specially-dug pit impoundment with progressive construction of the trenches and progressive rehabilitation of the filled trenches resulting in only a small area of tailings exposed to the elements at any time. Dry tailings management was assumed, as this allows construction of the cover as soon as a section of trench filled with tailings is completed. The trench cover consists of all the excavated material from the adjacent trench and would generally result in a cover thickness of more than 3 metres. For up to moderate rainfall climates zoning would probably not be required except that the topsoil should be separately stripped and placed over the soil cover to obtain the best revegetation conditions.

118 Figure 5 shows a ring dyke impoundment. The rehabilitation uses an internal drainage system directed to one "through-flow rock" spillway through which rainwater run-off is discharged to the natural surface. The required drainage pattern may be difficult to retain permanently due to larger settlements in the areas of deepest tailings.

119 Figure 6 shows a possible rehabilitation system for a valley dam tailings impoundment. Site conditions for such an impoundment will greatly influence the selection of a suitable drainage arrangement for the impoundment and its contiguous area.

120 Outer slopes of embankments of tailings 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 reactions with constituents of the tailings seepage water. This also applies to coarse materials in the embankments which will also be subject to natural weathering.

121 Conservative values are required for the factors of safety for the long-term embankment stability, usually slopes of 1 vertical to 10 horizontal should be used where the flattening of the embankment slopes is carried out using mainly soil material and not steeper than 1 vertical to 5

horizontal where the material used to flatten the slopes is mainly rock. Where steeper slopes are proposed an assessment should be given as to why flatter slopes are considered impracticable and the compensating factors and conditions identified which could make such steeper slopes acceptable.

122 The final rehabilitation proposal should include but not necessarily be limited to :

- a time schedule for all intended work up to the proposed date of termination of the owner's, operator's and manager's responsibility,
- the properties and quantities of materials to be used for the rehabilitation structures, and the locations from where such materials will be obtained,
- details of zoning of the cover structures and the rationale for each zone,
- expected settlements 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 water run off,
- 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,
- the estimated range of radon exhalation and gamma-ray emission rates over the surface of the rehabilitated tailings impoundment for the expected range of moisture contents in the tailings and the various zones of the cover structure,
- proposed surface revegetation procedures,
- estimated long-term life of the cover structure and basis for such a prediction, and
- monitoring and inspection program to be undertaken by the owner, operator or manager. This program would address such matters as:
  - 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 cover structure,
- radon exhalation and gamma-ray emmission from the tailings,
- rainwater runoff (quality and quantity),
- settlements of rehabilitated surfaces, and
- vegetation growth and fauna re-establishment.

123 Rehabilitation is a necessary final step after tailings impoundment. But what is done during impoundment can have major consequences in terms of the cost, ease and effectiveness of rehabilitation. Rehabilitation requirements may also place constraints on the methods used for tailings impoundment. It is necessary, therefore, that this guideline be followed in conjunction with the guideline on Decommissioning and Rehabilitation of Uranium Mine, Mill and Waste Disposal Sites.

REVEGETATION OF TAILINGS IMPOUNDMENTS

124 In designing the cover for the impoundment the appropriate authority should be consulted to determine whether or not the cover is to be vegetated. The latter case would normally only be considered in those areas where arid conditions prevail and the existing vegetative cover is sparse, non-existent or dependent on deep root systems.

125 Where vegetation is to be established its principal purpose is to provide additional protection against erosion either by wind or water while at the same time improving the aesthestic appearance of the area. However, in considering the establishment of vegetation it should be recognised that the cover is not a natural system. Therefore, a growing zone will need to be established which approximates a natural progression through horizons providing for runoff of excess rainfall, retention of moisture in the zone for plant growth and sufficient storage to sustain transpiration demands of vegetation through the variations in weather. In this regard, the initial site preparation of the tailings impoundment area should involve the stripping and stockpiling of the topsoil for later re-use. This topsoil will form the basis for developing the growing zone. The design of this growing zone should be undertaken by soil conservationists, in consultation with the engineers responsible for the cover design in order to ensure that the revegetation will not compromise the integrity of the cover.

126 At an early stage in the operation of the mill a trial impoundment which reflects all the conditions of the final impoundment should be constructed. This will allow the selection of the most suitable species and management requirements to achieve a self-sustaining vegetative cover. The selection of a vegetation type for the artificially formed cover structure may require consideration of plant types which are not natural to the site prior to disturbance.

127 For a detailed discussion of this topic refer to the guideline on <u>Decommissioning and Rehabilitation of Uranium Mine, Mill and Waste Disposal Sites.</u>

SELECTED REFERENCES

128 These references have been selected to provide a broad overview of methods and technologies which are, or may be applicable to the design, construction, operation and evaluation of tailings impoundments. It should be noted that new impoundment technologies are being continously developed and introduced.

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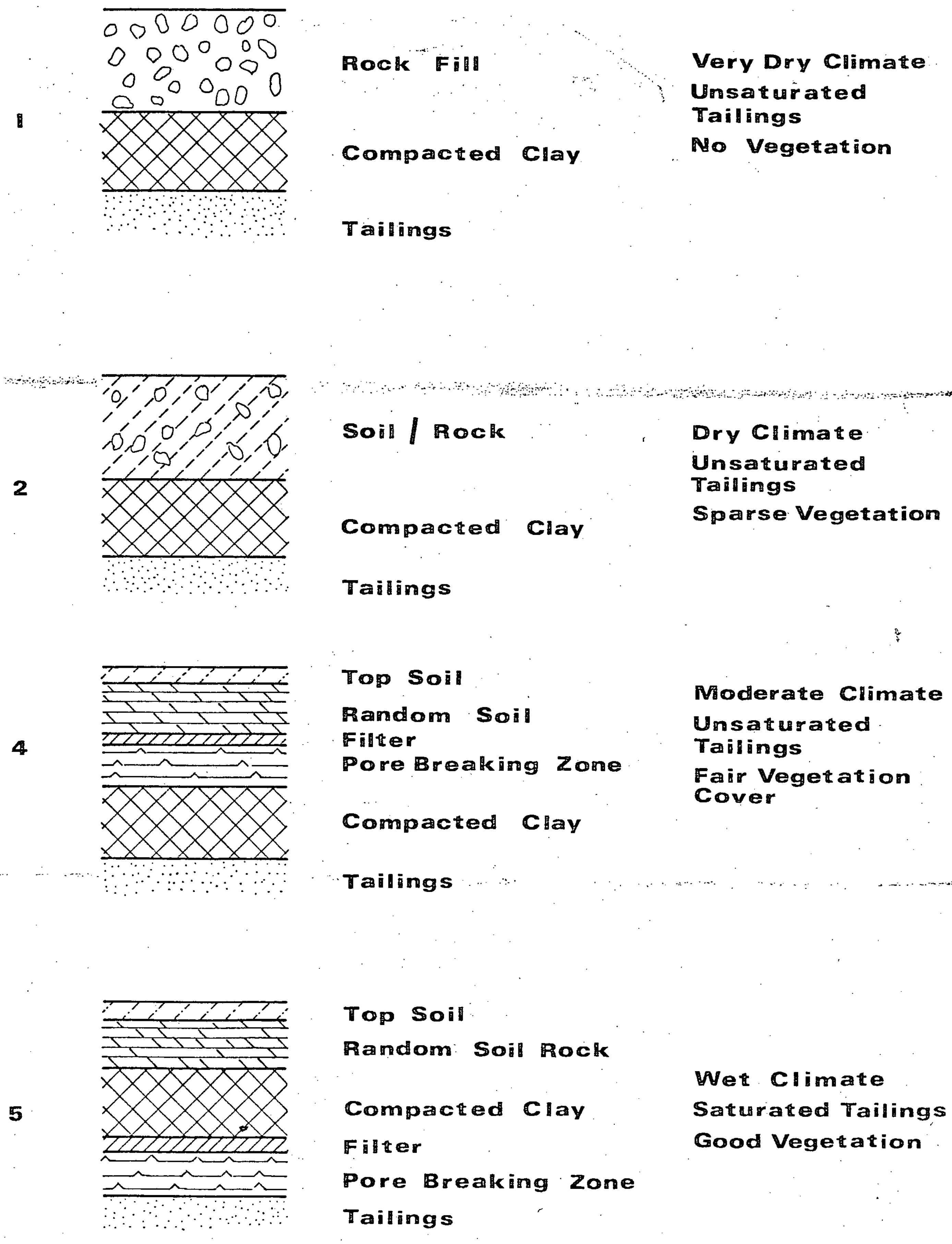
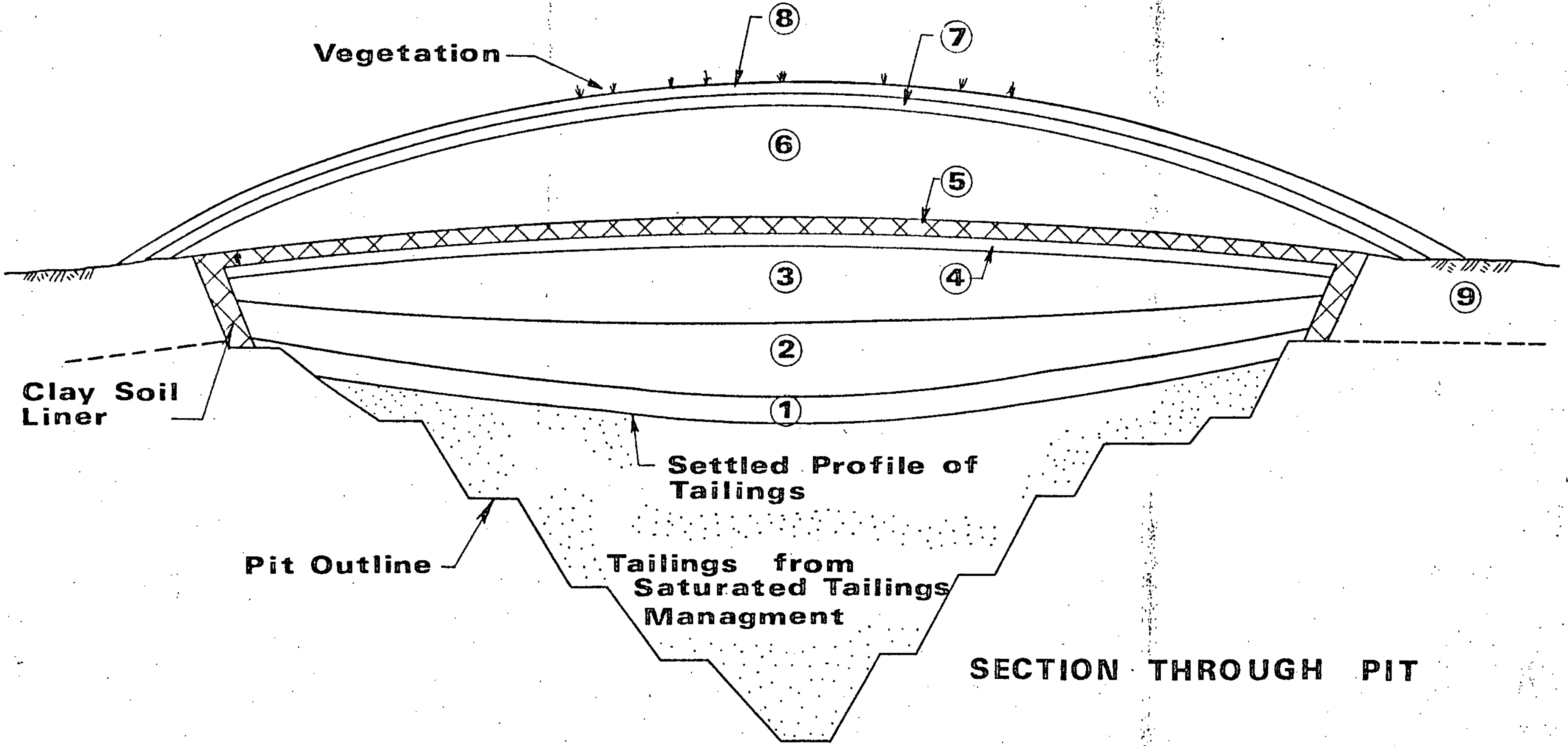


ZONING IN COVER STRUCTURES

Fig 1

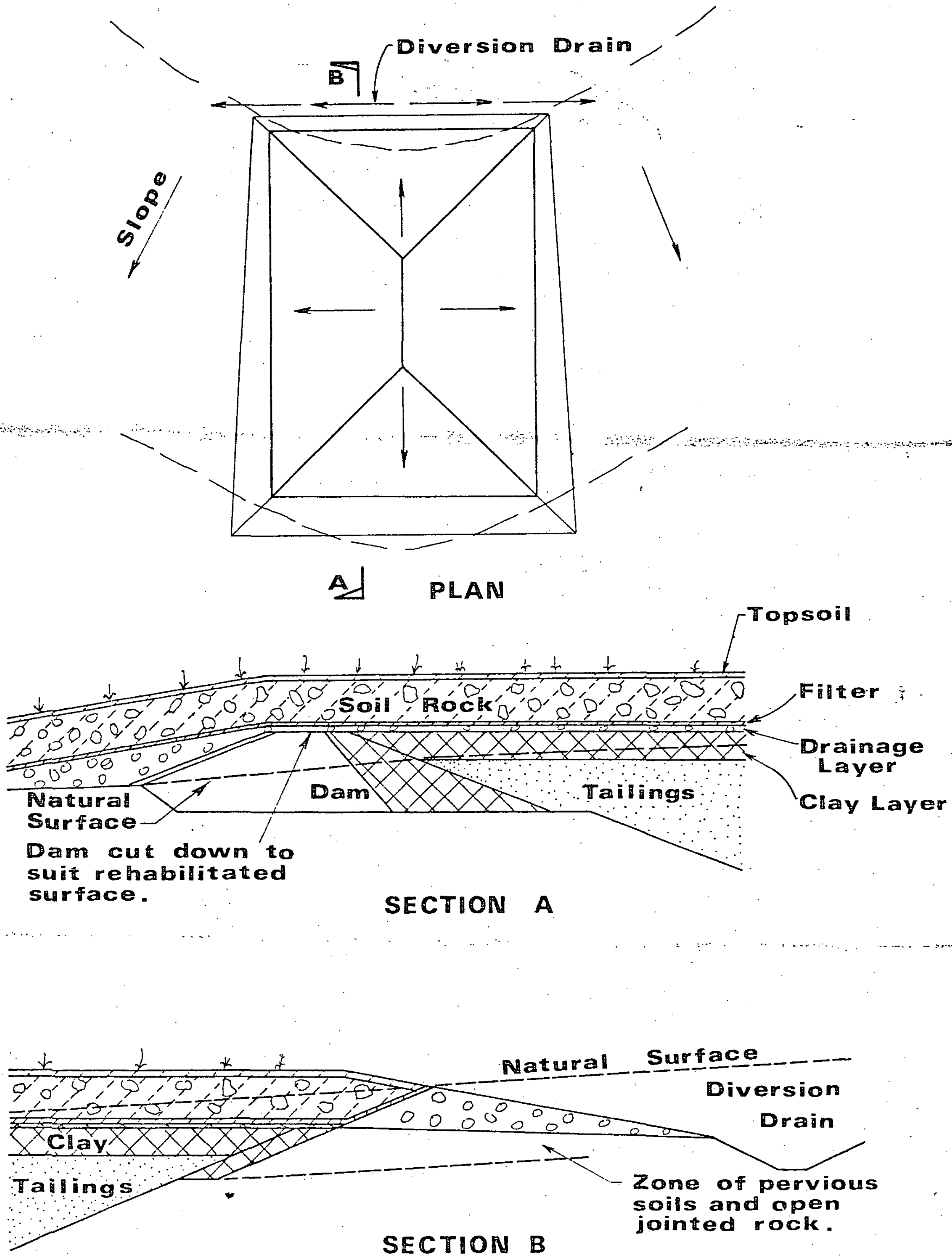


REHABILITATION BACKFILL

1. Bogum
2. Wastes from plant & water managment structures
3. Waste Rock
4. Gravel Soil Filter — 0·5m
5. Clay Soil Capping — 1·0m
6. Barren Waste Rock
7. Gravelly Soil — 0·5m
8. Soil & Top Soil — 1·0 m
9. Zone of pervious soils & open jointed rock

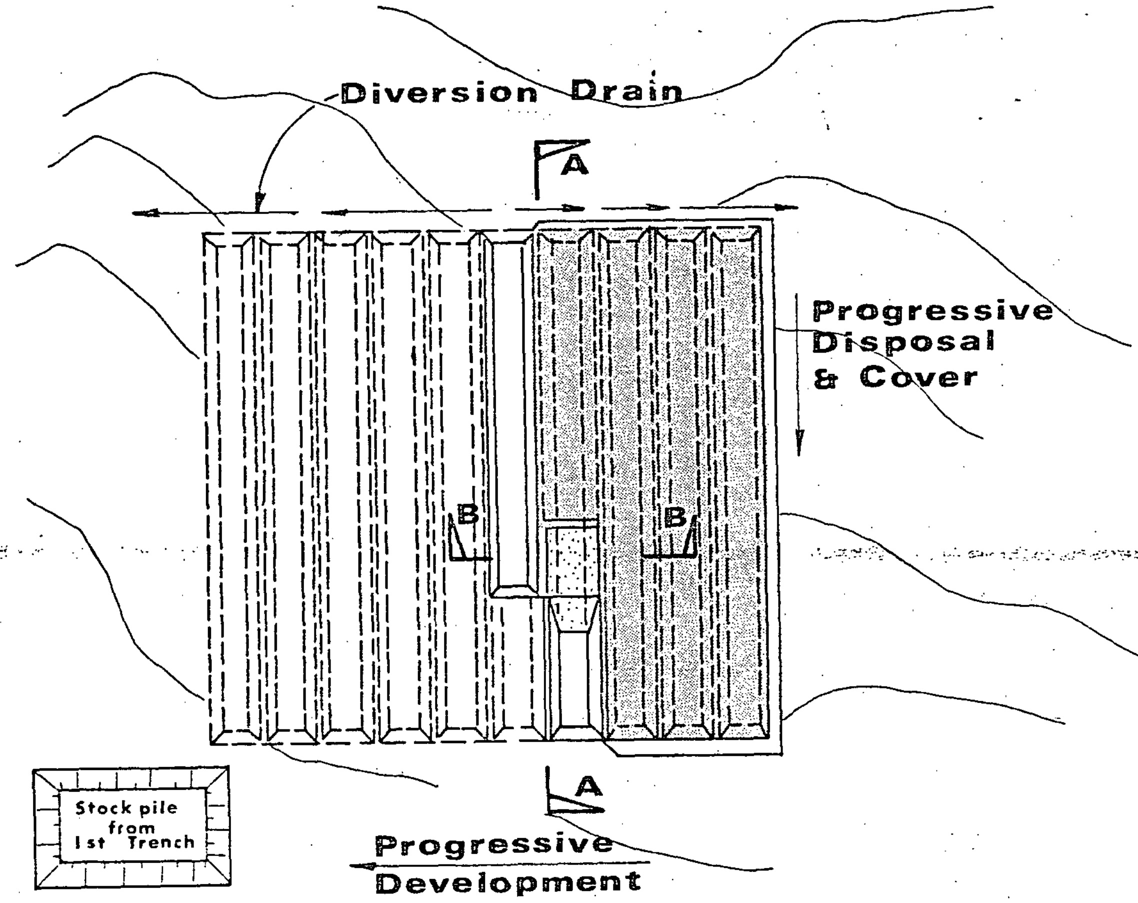
REHABILITATION FOR OPEN – PIT TAILINGS IMPOUNDMENT

Fig 2

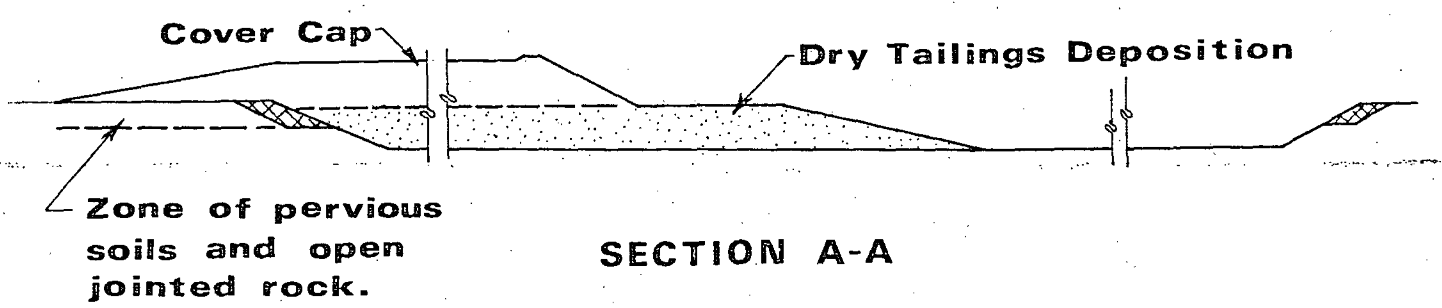


REHABILITATION
BELOW GRADE IMPOUNDMENT

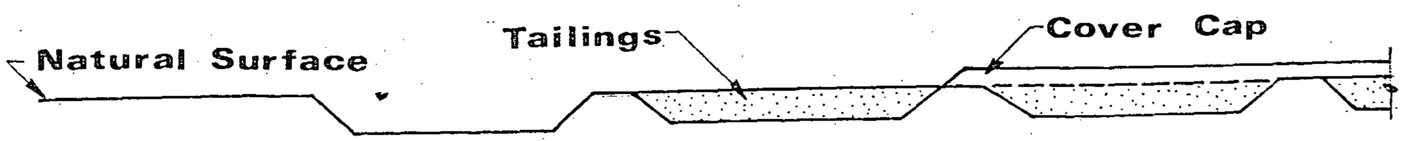
Fig 3



PLAN



SECTION A-A

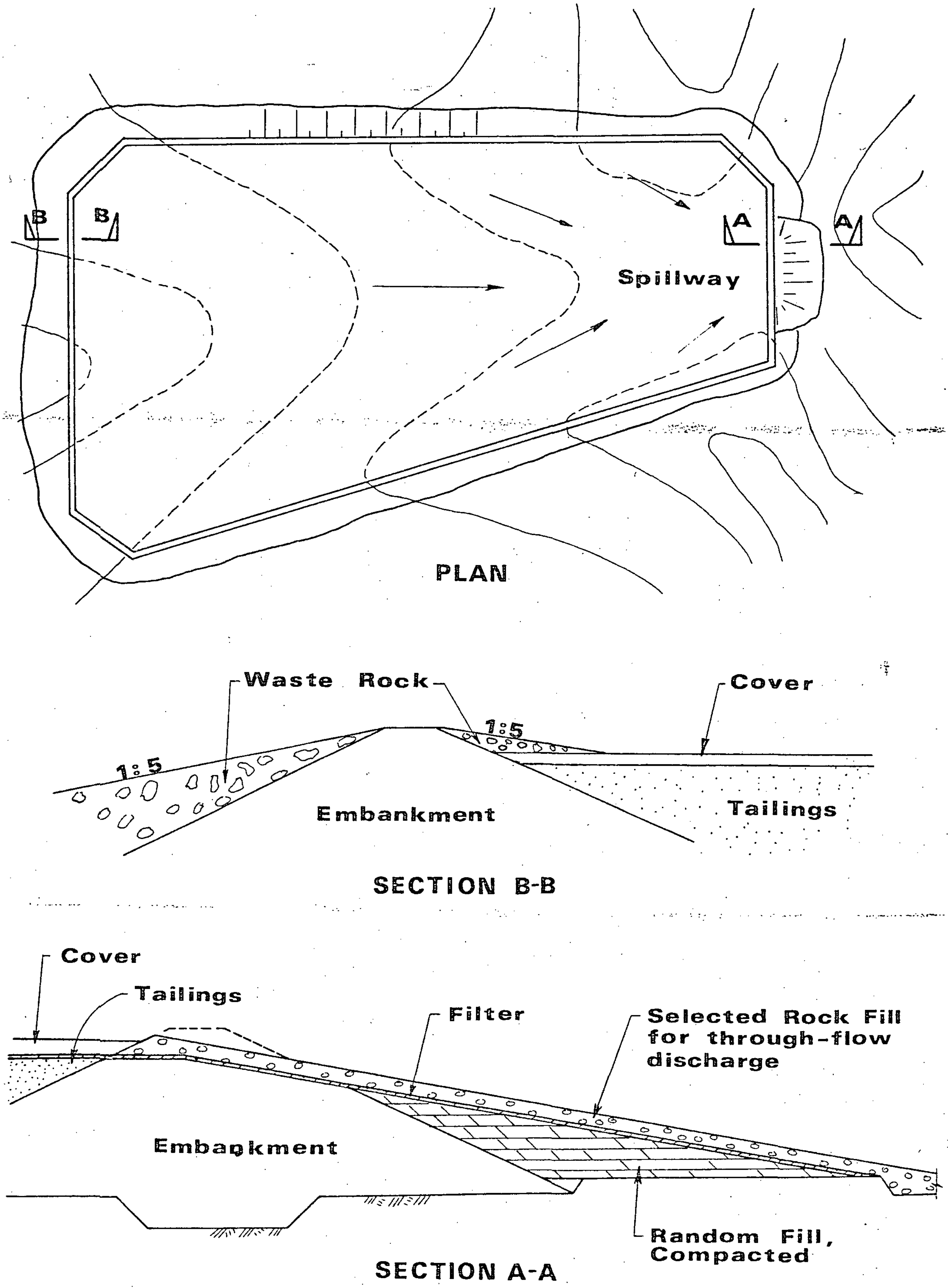


SECTION B-B

REHABILITATION
TRENCH IMPOUNDMENT

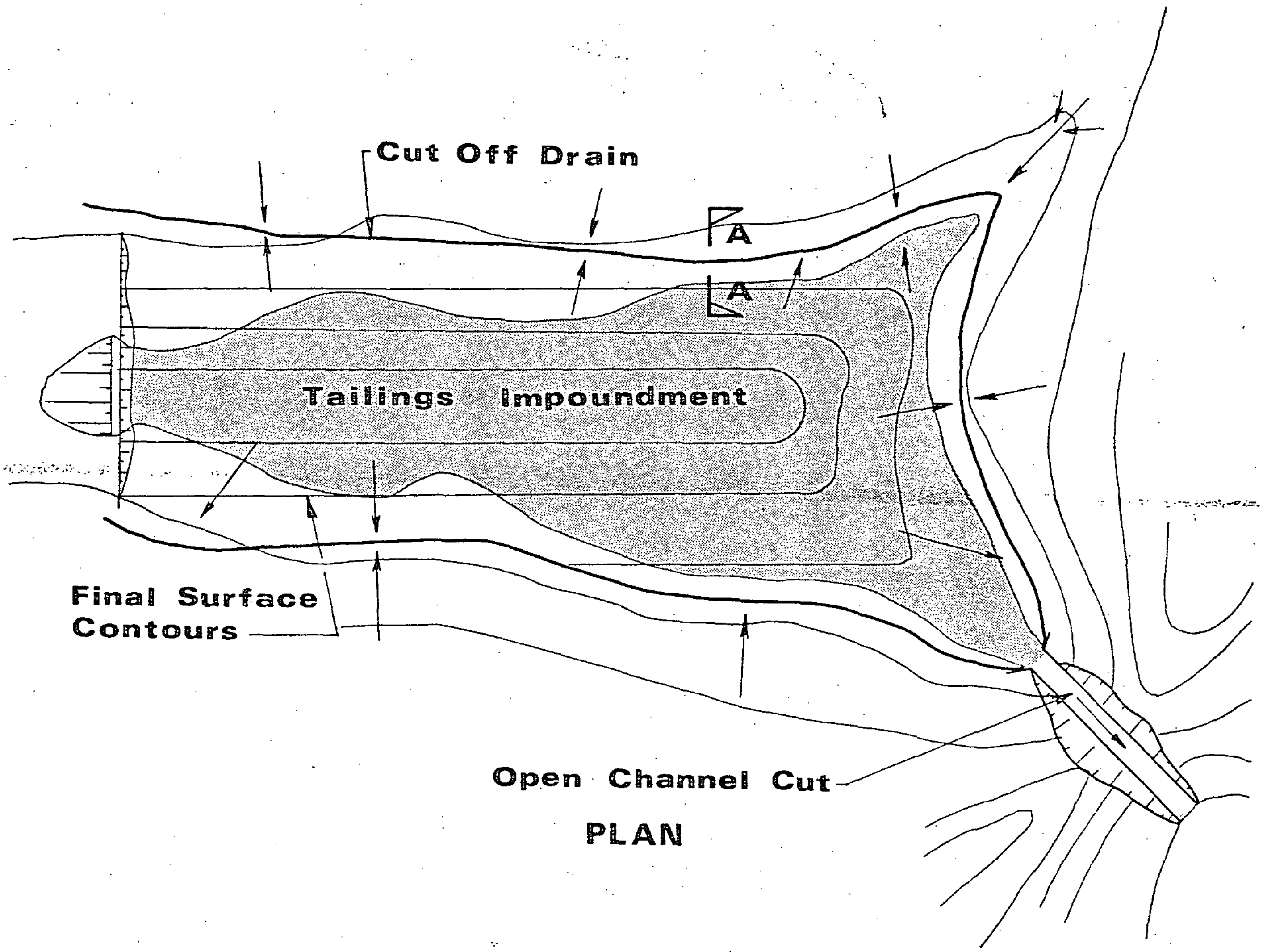
(Dry Tailings Management)

Fig 4



REHABILITATION RING DYKE IMPOUNDMENT

Fig 5



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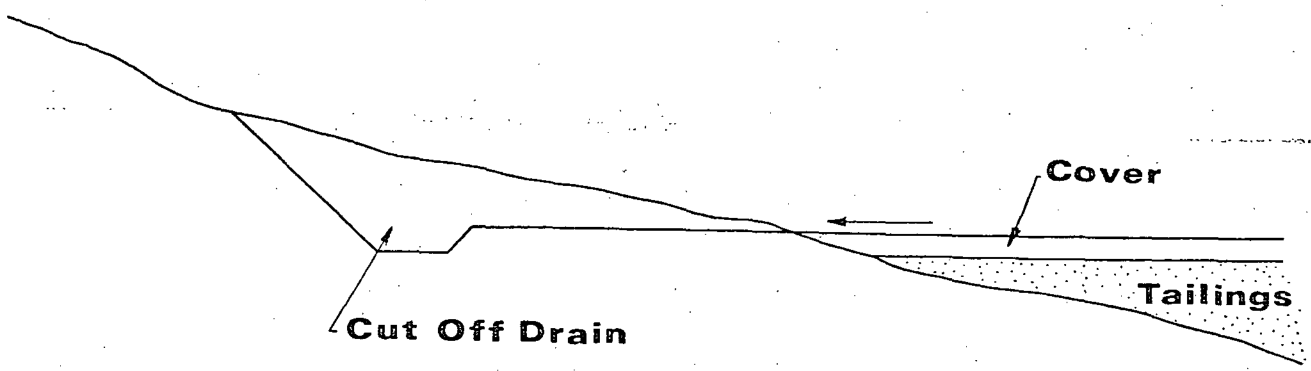

SECTION A-A

REHABILITATION
VALLEY DAM IMPOUNDMENT

Fig 6