Site selection and design options for uranium mine waste and plant tailings

by

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Synopsis

Intense public concern regarding the environmental and health effects of uranium tailings has forced a re-evaluation of past disposal practices. Consequently, site selection and design methods for uranium tailings have undergone considerable change and development in recent years. While South African tailings-management technology has contributed significantly to these developments, its public and regulatory review is not, as yet, as extensively developed as in most other major uranium-processing countries. This paper outlines the options that should be considered in selecting the site for, and the design of, the most economic and environmentally acceptable impoundment of tailings.

A site selection method is described that ensures the consideration of all reasonable siting alternatives within a given radius of the plant site. Methods of qualitative and semi-quantitative evaluation of the alternative sites are mentioned that permit the sites to be rated according to visual, land-use, pollution-risk, and cost criteria.

Alternative impoundment designs that are reviewed include embankments and diversions, liners, covers, and stabilization methods. Physical and chemical methods of tailings preparation that reduce the potential for pollution are considered briefly.

Introduction

Environmental and health concerns regarding uranium mining and milling wastes have been responsible for a continually increasing public anxiety. Although the radioactivity of these wastes is generally extremely low and of natural origin, the mining and treatment processes require that the radioactive ore should be brought to the surface, changing its form and increasing its mobility. This enhances the potential for the release of contaminants and for man's exposure to nuclear radiation. Exposure to radionuclides released from a tailings impoundment, while small as applied to any one generation, can be made large if taken far into the future — large enough to be the dominant source of exposure from the nuclear-fuel cycle.

Increased concerns regarding the toxicity and contaminant potential of mine wastes, particularly for uranium, cyanided gold, arsenic-containing ores, and acid drainage, have forced a re-evaluation of the risk and acceptability of mining in many areas. Numerous areas in many countries have been effectively closed to various forms of mine development, not by economic restrictions, but because of these public concerns. Examples are the moratorium on exploration and mining for uranium in British Columbia, Canada, and the wilderness areas of Alaska. When site selection and impoundment design are undertaken, the methodology used must not only produce the optimum solution but must be clearly demonstrable to, and understandable by, the concerned public or government authorities contributing to the mining-permitting process.

This paper outlines some of the site-selection and design options that should be considered for the impoundment of uranium tailings, and describes a site-selection process that is systematic, rational, and objective. The steps taken and the criteria used are defined to enable the methodology to be understood in the review and hearing procedure that is becoming more universally adopted in the permitting process.

Siting and Design Options

Four broad classes of siting and design options are available in the selection of sites for the impoundment of tailings. These are as follows:

1. site selection,  
2. site preparation and design,  
3. physical preparation of tailings, and  
4. chemical preparation of tailings.

The benefits of each option are highly specific to the site, ore, and country, and a combination of options considered best for one site is unlikely to be equally favourable for any other site.

Ore Characteristics

The nature of uranium ore varies widely. Obviously, the ore grade influences the radioactivity of the resulting tailings. Thus, the high-grade ores of
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Saskatchewan engender a different level of concern from that associated with marginal ores from which uranium is extracted as a byproduct, as in South Africa. The hard-rock quartzitic ores from the Elliot Lake mines and the South African gold-uranium ores grind to silt-sized silica particles, which are more easily and effectively belt-filtered than the ores of Wyoming with their higher, often bentonitic, clay content. Other chemical compounds that are associated with some ores, such as arsenic, may require special chemical conditioning of the tailings.

Site-specific Conditions

Site-specific conditions are generally recognized as controlling the effectiveness of most of the design options. The local balance between precipitation and evaporation determines the potential for a zero surface-water discharge system. Thus, zero-discharge systems can be implemented in areas such as the Highveld of South Africa but are not as easily attainable in the Elliot Lake region of Canada. If natural geological liners are absent, then either a lined impoundment or a dry tailings system is generally required. Thus, the substantial number of design options that can be, or must be, implemented are dictated by the conditions prevailing at the site selected. Because conditions generally vary considerably between sites, even when these are in close proximity, the careful selection of the site with the greatest advantages is a major design option.

Mining and Milling Influence

Designs for tailings impoundments should not be made in isolation from mining and beneficiation considerations. Some influences are obvious. Where the treatment plant is located close to an open-pit or underground mine, the return of the tailings to these below-grade facilities may be considered. A mine produces a large quantity of rock or soil waste that can be used to considerable economic advantage to implement a range of design options. The chemical processes used in the plant directly influence the quality of the tailings. Some influences are less obvious. The mining method and plan adopted for the open pit influence the cost of pit preparation for below-grade disposal. Metallurgical processes in the plant influence not only the chemical quality of the tailings but also their physical condition.

Mechanism of Contaminant Release

The suitability of a site or design option depends substantially on how effectively the release of contaminants is prevented both in the short and the long term. Mechanisms of release can be grouped into three basic modes:

(a) release due to the movement of surface solids such as by spillage, erosion, stability failure, and controlled or uncontrolled release of solutions,
(b) release due to seepage or leaching of the tailings solution or ground-water flow through the tailings impoundment, and
(c) release due to the air-transportation of particulate matter containing radionuclides or radon.

Detailed release mechanisms and concepts to minimize the risk of pollution are considered by Robertson et al.1.

Site Selection

The locations of the treatment plant and the tailings-impoundment site significantly influence both the capital and operating costs at a mine. Past practice has been to optimize this site selection based largely on criteria of economics and ease of operation, resulting in a relatively simple selection process. This selection process has now become more complex as a result of the numerous environmental concerns that limit the suitability of many sites.

Because of the long-term nature of the pollution and environmental impact of many tailings products, the selected site and engineered impoundment must serve as an effective containment facility not only in the short term but also in the very long term. Such long-term stability is an extremely difficult task to engineer into a facility subject to the slow but perpetual geological processes such as wind and water erosion, chemical and physical weathering, seepage, and leaching. Natural features on or surrounding some sites provide a natural ‘screen’ or ‘barrier’ to such forces or processes in a manner that cannot be achieved through engineering or construction.

Site selection represents one of the most powerful tools available to the engineer in ensuring the long-term stability of a tailings impoundment. The site-selection process is conveniently divided into two phases, each with a number of tasks.

Phase 1, Preliminary Evaluation

Task 1.1 Regional screening
Task 1.2 Identification of sites
Task 1.3 Analysis of fatal flaws
Task 1.4 Investigation of remaining sites
Task 1.5 Qualitative evaluation and ranking
Task 1.6 Semi-quantitative evaluation and ranking
Task 1.7 Cost analysis
Task 1.8 Selection of alternatives for detailed investigation

Phase 2, Detailed Investigation and Evaluation

Task 2.1 Detailed investigation of selected sites
Task 2.2 Conceptual designs for the sites
Task 2.3 Evaluation of costs and pollution risks for each site
Task 2.4 Ranking of sites and selection of prime sites
Task 2.5 Preparation of reports and documentation suitable for review process.

This methodology and the criteria used in the selection of sites for uranium tailings have been described by Robertson et al.1. Only some aspects are considered here.
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After regional screening, all possible impoundment sites are identified by the consideration of each area on the map that was not excluded from the regional screening. The following types of impoundment are considered in the identification of sites:

(a) valley dams,
(b) ring dykes,
(c) backfill in open-pit or underground mines,
(d) specially dug pits, and
(e) deep lake disposal.

After all the potential sites for tailings impoundment have been identified, a screening study is made of each site to eliminate those with ‘fatal flaws’. A fatal flaw is any site characteristic that is so unfavourable or severe that, if taken singly, it would eliminate that site as a potential tailings site. A typical list of fatal flaws is given in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
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<tr>
<td><strong>Fatal-flaw screening criteria</strong></td>
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<tr>
<td><strong>Visual</strong></td>
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<tr>
<td>1.1 Unacceptable visual impact</td>
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<tr>
<td><strong>Land Use/Ecological</strong></td>
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<tr>
<td>2.1 Endangered species</td>
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<td>2.2 Critical wildlife or fish habitat</td>
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<td>2.3 Sensitive or unique ecosystems</td>
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<td>2.4 Important recreation areas</td>
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<td>2.5 Historical and archaeological sites</td>
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<td>2.6 Mineralization (economical)</td>
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<td>2.7 Man-made features, e.g. oil wells and pipelines</td>
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<td><strong>Airborne</strong></td>
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<tr>
<td>3.1 Dust/erosion — high wind exposure</td>
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<td>3.2 Radon — proximity to human habitation</td>
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<td><strong>Seepage</strong></td>
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<tr>
<td>4.1 Foundation (unsuitable for placed liner or as a natural liner)</td>
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<td>4.2 Ground-water discharge or important recharge area</td>
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<td>4.3 Flood plain</td>
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<td><strong>Stability</strong></td>
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<tr>
<td>5.1 Topography (too steep)</td>
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<tr>
<td>5.2 Faults (active)</td>
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<tr>
<td>5.3 Upstream drainage area (too large)</td>
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<tr>
<td>5.4 Foundation conditions (poor)</td>
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<tr>
<td><strong>Operational</strong></td>
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<tr>
<td>6.1 Capacity (too small)</td>
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<td>6.2 Access (too difficult)</td>
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<td>6.3 Technical feasibility (not implementable)</td>
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<tr>
<td><strong>Cost</strong></td>
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<td>7.1 Development cost (uneconomic project)</td>
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The remaining sites are evaluated individually. All the available published data are reviewed and the site is visited. An inventory and assessment are made of all the factors that may influence the suitability of the site. These inventories can then be used to make a qualitative evaluation of alternative sites. The assessment process and the relative weight or importance assigned to the various characteristics are largely dependent on the personal preference of the reviewer.

In the qualitative evaluation performed as Task 1.5, no attempt is made to quantify or weigh the various characteristics. The evaluation is therefore largely dependent on the concerns and appreciation identified in the mind of the reviewer. It can be expected that the results may differ substantially when the evaluation is performed by different people.

In Task 1.6, an attempt is made to assign some specific values and a numerical methodology to this evaluation process. Two different methods are used.

1. **Rating of the site suitability based on visual, land-use/ecology, and operating factors.** The qualitative descriptions are assigned numerical values, which can then be added and averaged to give an overall numerical rating for each site.

2. **Rating of the site suitability based on pollution release factors.** The ‘risk of pollution’ from each of the contaminant-release mechanisms, previously identified, is dependent on each of three variables:

   (a) the likelihood that a release will occur,
   (b) the magnitude of the release when it occurs,
   (c) mitigation factors that will reduce the potential impact when the release takes place.

If a semi-quantitative estimate of the likelihood \(L\), magnitude \(M\), and mitigation \(Mit\) is assigned for each release mechanism as discussed below, then the risk of pollution can be determined as follows:

\[
\text{Risk of pollution} = L \times M \times Mit
\]

Likelihood relates to the chance that the release will occur given the specific site and design characteristics of the impoundment being considered. The likelihood of some releases is very high — such as the spillage of dry tailings during truck transportation. For other releases, the likelihood is very low — such as releases due to embankment failures. Robertson et al.\(^4\) have listed some of the factors that influence the likelihood of release.

Magnitude of release is the expected amount of tailings released if the release occurs by that mechanism from the specific site and conceptual design considered. Small releases are associated with failures in the transport system and in the embankment retaining dry tailings, etc. Large releases occur with embankment failures involving wet tailings, severe long-term erosion due to concentrated water flow, etc.

Mitigation occurs as a result of circumstances that reduce the impact of pollution following a release of any magnitude. No mitigation occurs where spoilage releases take place directly into a flowing river supplying a major urban centre. Considerable mitigation applies where a similar-sized release occurs by seepage downwards from an impoundment towards the water table where (a) the geochemical characteristics of the soil through which flow occurs retard the transportation of contaminants, and (b) the ground-water is of poor, unpotable quality.

Following an assessment of these factors, a rating of 1 to 5 is assigned to each. By use of the previous equation, an overall rating is determined for the risk
of pollution by that mechanism. A semi-quantitative comparison can then be made of the risk of pollution from all the mechanisms for each site and design option.

**Site Preparation and Design**

Site preparation and design options have been discussed by Robertson and Van ZyF.

**Embankment and Diversion Options**

Options exist regarding both the materials used and the type of construction. In South Africa, because of the generally low radioactivity of the tailings product and the suitability of the climate, tailings impoundment embankments are constructed of tailings using the upstream method. The use of both uranium tailings in the embankment and the upstream method of construction is not permitted in the U.S.A.

Erosion as a result of concentrated water flow presents one of the greatest risks for long-term release. Particular care must therefore be paid either to the avoidance of concentrated water flow locations (i.e. valley dams) or to the implementation of very secure long-term diversion options.

**Liner Options**

Two basic philosophies of seepage control exist: (i) containment using a liner, and (ii) limiting solutions available for seepage by tailings conditioning (drying). Neither of these concepts can be applied in the absolute form. All liners possess a finite permeability, and ‘dry’ tailings contain some moisture. Seepage losses are, therefore, an inescapable fact. Fortunately, the environment can accept seepage at a finite rate or to a finite volume. The rate or volume that can be accepted depends on the absorptive and purifying characteristics of the materials through which seepage occurs; the degree of attenuation, dilution, and dispersion along the flow path; and the demonstrable ‘low’ environmental impact on the downstream environment. Acceptable values are highly site specific.

While a number of liner options exist, there are generally three basic groups that are fairly generally applicable:

(a) geological liners,
(b) clay liners, and
(c) synthetic liners, including synthetic membranes,

Gunite, asphaltic concrete or sprays, and compacted soils or soil cement. Where there are natural geological liners on the site in the form of soil or rock strata of low permeability that can be incorporated in the tailings impoundment, they are usually an economical, effective seal. Many South African slimes dams sit on a natural clay liner of ‘black turf’.

Clay liners have been used more frequently recently, and some difficulties with chemical deterioration and construction control have been experienced.

Synthetic liners have proved difficult to install over large areas without construction imperfections. Current experience with these is that they can be very effectively used under the correct field and installation conditions for smaller impoundments, but their application to large impoundments and for long-term effectiveness is questionable.

The tailings themselves can be used to produce a liner. If the tailings are placed in an appropriate way, the tailings can be made to produce a layer of slimes on the floor and sides of a basin. This ‘slimes liner’ is particularly useful where there are few, if any, natural geological liners.

The effectiveness of a liner can be improved by the installation of a drainage layer above the liner, so reducing the effective head acting on the liner.

**Cover Options**

The cover has three primary functions:

1. To prevent the particulate dispersion of tailings due to wind erosion.
2. To prevent the exhalation of radon, and
3. To physically isolate and protect the tailings in the long term.

Functions (1) and (2) can be effectively achieved during the operating life of the impoundment by keeping the tailings wet or submerged. Long-term stabilization and reclamation usually require a substantial depth of soil cover.

**Stabilization Options**

After decommissioning, tailings impoundments should be left in such a condition that the likelihood of future disruptive forces is as small as possible. Nelson and Shepherd have stated that the major causes of long-term instability are water and wind erosion. The most effective design options for protection against these can be effected during site selection. Additional design options such as contouring, revegetation, rock armouring, and drainage are required to suit site-specific conditions.

**Physical Preparation of Tailings**

The state in which the tailings are placed in the field considerably influences the likelihood and magnitude of potential releases.

‘Wet’ tailings, containing an excess of tailings solution, behave essentially as a fluid and their impoundment serves essentially as a dam. The following characteristics apply.

(a) The geometric shape limits suitable sites and methods of reclamation.
(b) There is an excess of solution available for seepage.
(c) Reclamation of the impoundment can generally be initiated only once tailings placement stops.
(d) A breach of the impoundment embankment generally results in a large discharge of tailings solution and liquified tailings.

‘Dry’ tailings behave as a damp, granular material. They may be placed in a pile and have little solution free to drain under the action of gravity alone. The following characteristics apply.

(i) The tailings can be placed in piles and almost any geometric shape achieved, giving consi-
derable freedom for the location of impound-
ments.

(ii) Little solution is available for seepage loss or
discharge.

‘(iii) Reclamation of the impoundment can be
done concurrently with the placement of the
tailings, minimizing the area of impact and
the cost of reclamation on decommissioning.
(iv) Containment embankments are not required,
and breaches with large releases of tailings
cannot occur.

The techniques, equipment, and economics
applicable to the production of dry tailings have
developed extensively over the past few years,
substantially as a result of the implementation of dry
tailings in coal and uranium mining. Options that
should be considered include the following:
1. thin-layer leaching* (gravity drainage)
2. sand-slime separation* (cyloning)
3. suction dewatering (belt, drum, or disk
filters)
4. pressure dewatering* (filter and belt presses).

‘Semi-dry’ tailings are achieved when wet tailings
are discharged into an impoundment in a controlled
pattern. By the appropriate control of the location
and size of the pool, and through the use of a
suitable underdrainage system, an effectively ‘dry’
tailings pile can be achieved by the time of decom-
misioning. The traditional technique used for the
building of gold-uranium slimes dams in South
Africa is a partial application of the management
techniques for semi-dry tailings.

The selection of an appropriate system for the
conditioning and field management of tailings is
crucial to the implementation of the most cost-
effective and environmentally acceptable solution at
a particular site.

Chemical Preparation of Tailings

Large quantities of chemicals are required in the
extraction process and, because many of these
chemicals may have a marked impact upon the
quality of the surface or ground water, the selection
of the overall treatment process should not be made
solely on hydrometallurgical grounds.

The selection of an acid or an alkaline leaching
process makes little difference in terms of the
radioactive impact on the environment. Tailings
from either process contain very similar amounts of
$^{226}$Ra and thus emanate similar quantities of $^{222}$Rn.

The major constituents in effluents discharged from
the tailings impoundment are the chemicals
required for the dissolution and subsequent concentra-
tion of the yellowcake product. It is often
preferable to change the process chemicals rather
than to institute costly treatment systems. Examples
exist of such process changes, and studies are
currently being made of methods for the extraction
of radionuclides$^{10}$.

Conclusions

Twenty-one years ago, few of the site selection and
design options described in this paper were applied.
Today many of them are applied routinely, and an
entire engineering specialization has developed for
the design of tailings impoundments in general and
uranium tailings impoundments in particular. This
increased engineering effort has been required largely
to increase the safety of tailings dams and to reduce
the potential for short-term pollution. Increasingly,
the public and health authorities are becoming
aware that there is a need to protect and engineer
not only against the large catastrophic releases of
tailings, but also against the slow releases that occur
over a very long period. Such slow releases become
cumulative from the increasingly large volumes of
tailings being produced. The most cost-effective
control measure is appropriate site selection. After
that, there are a number of alternative additional
measures that can be considered to minimize long-
term releases. It is the engineer’s responsibility to
design impoundments not only for twenty-one years
hence but also for at least twenty-one times twenty-
one years hence.

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P.J. Broad: Are there any known differences in bacterial agents world wide that would determine the type of system used?
O.K.H. Steffen: I do not know.

J.H. Truter: For existing reduction works, what should one do to control tailings disposal?
O.K.H. Steffen: The most important action necessary in my view is to institute a monitoring programme to identify any pollution and the trends that may be established over the life of the dam. Because one is interested in trends, the earlier a monitoring programme is started, the more valuable the information obtained. The cost of a well-planned monitoring programme is very small, while the benefit can be very large indeed.

A major objective of tailings management is the effective closure of the dam at the end of the life of the mine. Certain construction measures can be instituted at an early stage that would allow for the long-term stability of the tailings dam at no additional cost to the mine. Tailings deposits that have not been planned with the eventual closure requirements in mind should be reviewed, and measures should be adopted that would minimize the costs of construction required to meet the closure standards.

D.A.M. Smith: A problem in establishing monitoring after waste disposal has been operative for a number of years is that it is difficult to establish a baseline against which performance can be assessed, since baseline values for the parameters of interest will have changed because of these operations. It may be necessary, therefore, to extend monitoring outside the immediate area of the tailings dam to establish a realistic picture of pre-disposal conditions.