EXHIBIT / FOOT NOTE
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Study of Tailings Management Technologies

MEND Report 2.50.1

This work was done on behalf of the Mine Environment Neutral Drainage (MEND) Program and sponsored by:
The Mining Association of Canada (MAC) and MEND

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MEND Secretariat

Mine Environment Neutral Drainage (MEND) Project

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EXECUTIVE SUMMARY

Introduction

Facilities built to store mine tailings pose both physical and geochemical risks that must be managed throughout the life of the facility, from design and construction, through to the closure of the mine and beyond. In Canada, most mines manage their tailings as a slurry deposited behind containment dams (designated in this report as "conventional tailings facilities"). In the wake of small and large-scale tailings facility failures, the risks posed by conventional tailings facilities are coming under increased scrutiny. Although one root cause has not been identified for all tailings dam failures, a common contributing factor to the higher consequence of failure includes the storage and behaviour of water within the facilities. This has led the industry to reconsider alternatives to conventional tailings facilities, including dewatering tailings prior to deposition (e.g. thickened, paste and filtered) as well as different facility types (e.g. downslope, cone, and "dry" stack/pile).

The objective of tailings management is to safely store tailings and reduce the risks, particularly over the long-term. To this end, "dry" closure significantly reduces physical risk and needs to be balanced against potential geochemical risks. Tailings planning and operation should be focused to long-term post closure considerations and as such should be a primary consideration when assessing potential technologies and facility types.

Driving the interest in dewatered tailings is a desire to reduce the physical risk posed by conventional tailings facilities. Although the technology exists to build safe dams, the industry has not been able to achieve zero failures. Currently, creating paste and filtered tailings for disposal is more costly than conventional tailings, unless other factors are important cost drivers: dam cost, water cost, a lack of community acceptance, or the fact tailings would be better stored underground.

Turning slurry tailings into paste has been an industry and research focus for more than a decade, but it has not achieved broad acceptance in the industry. More recently, interest has moved towards filtered tailings; costs are decreasing and larger throughput plants are being proposed. These innovations may make filtered tailings an increasingly attractive, lower-physical-risk option compared to conventional or paste tailings. However, other factors need to be considered when selecting a tailings management strategy (e.g. site conditions, geochemical risks, long-term closure risks, environmental impacts and social impacts).

This report presents a snapshot of the current state-of-practice in the Canadian mining industry. It looks at the technologies used to dewater tailings, how tailings are placed and managed, and evaluates their relative efficacy in addressing physical and geochemical risks. It also identifies opportunities for further research and development. The reader will gain an understanding of the strengths and limitations of tailings dewatering technologies, deposition practices, and how these choices apply to specific sites and mining projects compared to conventional practices. The report should help guide which technologies and strategies should be considered for a project, taking into account site conditions, project constraints (e.g. production schedule), tailings' physical properties (e.g. grain-size, and plasticity), and geochemical properties (e.g. the potential for tailings to generate metal leaching (ML) and/or acid rock drainage (ARD)).

A tailings management strategy considers many aspects of disposal, including; facility types (e.g. conventional, thickened/paste, filtered), tailings technologies (e.g. segregation, co-disposal, in-pit or underground backfill, dewatering - thickening and filtering, etc.), and operational, environmental, socio-economic, and closure considerations. This study focuses on tailings facility types and dewatering technologies and presents an assessment of alternative tailings technologies and facility types in comparison to conventional slurry facilities.

More specifically, this study aims to (1) present the use of dewatering tailings technologies and associated facility types alternative to conventional in Canada (or in other locations with similar climates), (2) evaluate the applicability and efficacy of the alternatives at reducing physical and geochemical risk compared to conventional tailings facilities, and (3) identify opportunities for further research and development. This study is not exhaustive and does not assess all alternate tailings management strategies or considerations (e.g. social considerations), nor the various types of dams, dikes and retention structures, which are also a key component to tailings management technologies and approaches.

The following approach was applied for this study:

- Step 1 - Identify the current state-of-practice and projects using alternative technologies in Canada through literature review, database research, and a questionnaire sent to all Canadian mine sites.
- Step 2 - Evaluation of the alternatives, comparing tailings management technologies and costs using the information compiled as part of the identification of the current state-of-practice and the case study information provided by select mine sites.
- Step 3 – Assess applicability to Canadian mines and identify knowledge gaps. Lessons learned from the case histories in the context of mining in Canada were summarized and knowledge gaps identified for further research.

Dewatering of Tailings and Facility Types

The state of dewatered tailings is a continuum that ranges from a fluid slurry (like water), to thickened (like molasses), to paste (like toothpaste) to filtered tailings (like a soil). The state of dewatered tailings is typically categorized based on the solids content (mass of solids to total mass of solid/liquid mixture) and the shear yield stress (or strength - the applied pressure that must be exceeded to make a fluid flow). Different types of dewatered tailings are stored in different types of facilities (e.g. conventional, high-density thickened/paste and filtered).

Conventional Tailings Facilities

Conventional tailings facilities involve delivery, often in a pipeline, of unthickened or thickened slurry (typically ~20% to ~40% solids content by weight, and up to 60%) from the ore processing facility or thickener to the tailings facility. The tailings are deposited hydraulically, in a loose state, behind containment dams. Tailings are deposited either above or below water and will typically segregate with coarser material settling near the discharge point and finer material being transported further from the discharge point. This segregation can be an advantageous or detrimental aspect of conventional deposition. Water liberated from the slurry collects in a pond on the tailings surface and (a) evaporates, (b) is discharged from the facility, or (c) is reclaimed to the ore processing facility.

Approximately 90% of Canadian mines are managing their tailings as slurry deposited in conventional tailings facilities.

Dams may be constructed from locally excavated material, mine waste rock, the tailings themselves, or a combination of materials.

This study does not delve into comparing the different types of containment structures and material types for conventional facilities (e.g. upstream, downstream, centreline, cycloned sand, waste rock). Containment dam design is an important part of risk management associated with tailings facilities that should also be considered during selection of a tailings management strategy.

High-Density Thickened/Paste Tailings Facilities

High-density thickened/paste tailings facilities involve delivery, in a pipeline, of a high-density thickened or paste tailings (typically ~60% to ~75% solids content by weight and shear yield stresses from 40 Pa to 200 Pa) to the tailings facility. Due to the high shear yield stress of the tailings, positive displacement pumps may be required. The tailings are deposited hydraulically, in a loose state, and beached at somewhat steeper slopes than unthickened slurry (in theory slopes can be up to 4%, however, in practice steep slopes are only achieved for a short distance and the overall beach often slopes at less than 2%). An aim of thickened or paste tailings deposition can be to reduce or eliminate the segregation associated with conventional slurry deposition.

Containment dams are still required, but can be smaller than those with conventional tailings facilities if beach slopes can be taken advantage of. High-density thickened/paste tailings facilities are usually operated with no or minimal ponds on the tailings surface. Compared to conventional tailings facilities, less water is released from the deposited tailings as they consolidate. This water, along with precipitation and runoff, collects in ponds on the tailings surface next to the dam, or is directed off the surface to external collection ponds where it may be reclaimed to the ore processing facility or discharged.

Similar to conventional facilities, the containment dam design for these facilities can vary and is not the focus of this study.

Historically, this is the least common facility type in Canada. Based on our research, consistency of tailings product over time and lack of ability to achieve steep tailings slopes are the main concerns with high-density thickened/paste tailings.

Filtered Tailings Facilities

Filtered tailing facilities involve delivery, by truck or conveyor, of tailings that are dewatered such that they are partially-saturated and act like a soil rather than a fluid. Filtered tailings are typically dewatered to more than 80% solids content and often close to the optimum moisture content (the moisture content at which the maximum density can be achieved through compaction). Typically, compacted filtered tailings are used for structural containment of the tailings facility. Seepage and runoff are collected and managed in external collection ponds.

Historically, this has not been a common facility type in Canada, likely due to the high cost traditionally associated with this method. However, more and more filtered facilities are being proposed and constructed in Canada.

Comparison and General Lessons Learned

Some general lessons learned from the research and case studies conducted as part of Step 1 of this study are summarised in Table 1 and Table 2.

Table 1 Considerations for all Types of Tailings Facilities

Topic	Consideration
Segregation Technology	Particle segregation (e.g. sulphide flotation) and separate management of sulphidic ML/ARD tailings can be environmentally and economically beneficial, particularly if implemented at the start of mining.
Water Management	Safe water management at all tailings facilities is a major requirement for both water quality and physical stability of the facility. Tailings facilities should not accumulate water on a long-term basis and should have appropriate water discharge permits and, if required, water treatment plants, to allow discharge of water. Site design, catchment area, technology selection and progressive reclamation should also be considered to help manage water balance.
Dust Management	Dust is a concern at all tailings facilities. Unthickened and thickened tailings allow the opportunity for continual wetting of exposed beach surface. Progressive reclamation of filtered piles provides an opportunity for reducing surface areas exposed to potential dusting, but areas that can't be reclaimed (e.g. large active deposition areas when using mobile stacking conveyors) may require active dust management.
Deposition	Placement of tailings in "exhausted" open pits and in underground workings can be a good tailings risk-reduction approach, both geotechnically and geochemically.
Risk and Consequence of Failure	Risk is the key consideration when designing, constructing and operating a tailings facility. Tailings facilities should be designed to minimize the consequence of a potential failure as much as possible. For example, not using a tailings facility for long-term water storage of the mine.
Closure	Tailings facilities should be designed for dry closure with appropriate land and water use and/or landform transition. The potential risk cost associated with the tailings facility during long-term closure should be considered within the selection process for closure design.
Risk and Life-Cycle Costs	During tailings management planning, the full risk profile of alternative tailings management strategies (including life-cycle costs) should be considered. This can be done through a structured assessment, such as Failure Modes and Effects Assessment (FMEA).

Table 2 Key Considerations for the Different Facility Types

Item	Conventional Tailings Facilities	High-Density Thickened/Paste Tailings Facilities	Filtered Tailings Facilities
Strengths	▪ Can be widely applied to different types of tailings. Processes are well known. ▪ Tailings, below 10 m to 20 m depth in the deposit, naturally consolidate to the similar in-situ density as high-density thickened/paste. ▪ Greater operational flexibility for overall mine water management due to the attenuation capacity on the tailings surface (including seasonal variability). ▪ Can provide saturated conditions for management of Potentially Acid Generating (PAG) tailings. ▪ If designed appropriately, can be closed as a "dry" facility.	▪ Higher water recovery during processing; less water to be managed at the tailings facility. ▪ May be non-segregating, producing a tailings product with potentially low hydraulic conductivity and high moisture retention capacity (can be used to control ML/ARD). Note, consistency will depend on the variability of the tailings properties. ▪ Paste tailings can be used as underground backfill where applicable. ▪ If designed appropriately, can be more easily closed as a "dry" facility than conventional tailings facility. ▪ Failure, if it occurs, would likely be local slumping and consequences would be restricted to the local area (or the distance equivalent to roughly 20 times the height[1]) unless the material slumps into a water body.	▪ May permit storage in areas with steep topography, space restrictions or other circumstances where a conventional tailings facility is impractical. ▪ Highest water recovery during processing is advantageous in regions where water is scarce. ▪ More flexibility for placement strategy and final configuration, which can allow for progressive reclamation. ▪ Most amenable to dry closure and landform development. ▪ Failure, if it occurs, would likely be local slumping and consequences would be restricted to the local area (or the distance equivalent to roughly 10 times the height[1]) unless the material slumps into a water body.
Limitations	▪ Not all conventional facilities are designed the same, and therefore, there are a range of risks associated with them. ▪ Although failures are uncommon, the consequence of failure can be large. There is a significant amount of management and design effort required over the long operational life of the facility to reduce risks to an acceptable level. ▪ The risks associated with upstream constructed dams can be underestimated	▪ High-density thickeners and filters require operational attention and are subject to system "upsets" from tailings variability, gradation, or operator error. ▪ It could take months to years to optimize the thickening system to produce a consistent tailings product and the achieved solids content is often at least 5% lower than the design target. ▪ Positive displacement pumps may be required for transportation, which are more expensive and more challenging to operate.	▪ May not be applicable to all tailings types in all situations (tailings with high clay-sized particle content are more challenging to filter to required moisture contents). ▪ Filters or filter plants require more operational attention and are subject to system "upsets" due to ore variability, gradation, or operator attention. Additional storage ponds are required in the case of system upset where filtering must stop.

[1] Estimate of runout distance included for comparison purposes only.

Item	Conventional Tailings Facilities	High-Density Thickened/Paste Tailings Facilities	Filtered Tailings Facilities
	and the low cost of these structures can dominate the decision process. ▪ Water management must be balanced to avoid storing too much water in the facility, while allowing for contingency storage for; shut down periods, routing of excess site water through the tailings, and other system upsets. Water management over the long lives of these structures may be difficult and upset conditions causing high pond levels is a key risk factor for conventional facilities. ▪ Segregation of tailings can be a problem for acid generation in beach sands and/or slow consolidation of slimes areas.	▪ Beach slopes are difficult to predict and will vary depending on operational practices, tailings properties, and weather. ▪ Significant drying time (if required for stability) is often not achieved in wet climates and may require a large drying area and rotation of the discharge points. ▪ Typically, the tailings facility does not provide adequate storage to attenuate seasonal water flows. Therefore, external water storage is required to effectively manage runoff and other site water. ▪ Precipitation and wind on slopes can lead to increased erosion. ▪ Little to no precedents for closure implementation.	▪ Trafficability of filtered tailings surfaces can be a challenge depending on tailings moisture contents from the filter plant and climate conditions. ▪ More challenging placement in wet and cold climates. Covered sheds are typically required for periods of wet weather when placement must stop. ▪ Deposition by conveyor or truck and shovel can be difficult to scale to higher tonnage rates. ▪ Still requires "structural zones" (which perform like dams), made of compacted tailings for containment. ▪ Requires external water storage to manage runoff and other site water. ▪ Precipitation and wind on slopes can lead to increased erosion. However, some filtered tailings facilities can be staged for progressive reclamation, which will help control erosion. ▪ Increased power usage. ▪ Difficult to manage sulphidic ML and ML/ARD using source control measures due to low saturation of materials. ▪ No precedents for closure, but may allow progressive reclamation.
Physical Risk	▪ **Highest during operations.** ▪ Reclaim pond in tailings facility during operations increases the consequence and likelihood of failure. ▪ Loose, saturated tailings have potential for mobility especially if pond water is released by a failure.	▪ **Highest during operations and closure.** ▪ Still requires some management of water on tailings surface. ▪ Tailings have potential for mobility (not compacted) and are not fully contained by a dam in the event of structural failure. ▪ Little precedents for large-scale operations.	▪ Risk of not being able to meet material specifications consistently during construction, which increases the likelihood of slope failures. ▪ No precedents for large- scale operations.

Item	Conventional Tailings Facilities	High-Density Thickened/Paste Tailings Facilities	Filtered Tailings Facilities
Geochemical Risk	▪ **Highest during operations and closure.** ▪ Where the tailings are sulphidic, oxidation and runoff or seepage through these pervious zones may result in ML or ML/ARD. However, there are case study comparisons (precedents) for successful management of ML/ARD. ▪ In the right climate, the ability to saturate the tailings to manage ARD is a key advantage of this disposal method. However, if tailings are not managed appropriately, and ML or ML/ARD occurs, more water management will be required.	▪ **Highest during operations and closure.** ▪ Small-scale operations can be successful and control ML/ARD with no ponded water, but large-scale operations have a higher risk of ML/ARD in comparison to conventional tailings facilities.	▪ **Highest during operations.** ▪ Partially-saturated tailings containing sulphides will oxidize and generate ML/ARD. However, effective compacting, staging and progressive reclamation (when possible) can help control ML/ARD and limit active water management. ▪ Large-scale operations have a higher risk of ML/ARD in comparison to small-scale operations or conventional tailings facilities due to placement methods.
Costs	▪ Typically, the lowest capital and operating cost option. ▪ If ML/ARD occurs, water management costs can be immense over time. ▪ Total life-cycle costs can be substantial if closure takes a long time and long-term active water management is required. ▪ Cost of failure can be immense.	▪ Typically, higher capital and operating cost option in comparison to conventional tailings facilities. ▪ If ML/ARD occurs, water management costs can be immense over time. ▪ Total life-cycle costs can be substantial if closure takes a long time and long-term active water management is required. ▪ Cost of failure could be significant, particularly if a large facility has a liquefaction failure. However, there are only a few large facilities worldwide and there is no precedent of extreme consequence failures.	▪ Typically, highest capital and operating costs. ▪ If ML/ARD occurs, water management costs can be immense over time if not progressively reclaimed. ▪ Facility should be able to be closed relatively quickly. ▪ Cost of failure should be less than the other facility types.

Knowledge Gaps and Recommendations on Further Study

In general, the main knowledge gaps derive from the lack of sharing of information and lessons learned, including failures or mistakes, which are also essential learnings. The key knowledge gaps and recommendations for further study have been organized into four categories: costs; closure; other technologies; and geochemistry.

Costs

- There is a lack of publicly available information on the cost of tailings management, from construction to closure and post-closure. Compilation of a structured database of costs would assist in communicating the life-cycle cost of tailings management and aid in future tailings management decision making.
- Life-cycle costs of tailings facilities generally address construction, operations, closure and post-closure. However, at the planning stage the closure plans are often not comprehensively developed, and closure requirements can change over the life of the mine. Additionally, the comparison of alternative designs and alternative closure scenarios may not specifically address the potential risk-profile of each alternative. Developing a structured risk-profile for tailings management alternatives would be beneficial in identifying acceptable/unacceptable risks and deciding on the preferred management strategy.

Closure

- Compilation of closure case histories for all types of tailings facilities would be beneficial. The performance and monitoring of dry covers is very important in geochemical management given the desire to close facilities without ponded water.
- An important objective for tailings facilities is to, over time, transition the facility into a natural-like landform or a sustainable land/water use facility. Further research into what features may be required or incorporated into the facility design, such that it could be eventually classified as a landform, and further definition of criteria for a landform, would be beneficial.
- Further research on the long-term potential mobility of tailings would be beneficial for tailings planners to understand the long-term risks and to help design to minimize those risks.

Other Technologies

- Sulphide flotation can help manage geochemical risks by reducing the sulphide content of most tailings and allowing for separate management of the smaller volume of the concentrated sulphide stream. Continued research into other processing methodologies that work towards reducing the concentration of metals and contaminants of concern in the tailings would be beneficial.
- Unconventional dewatering technologies are being researched but are not commercially in use because of cost (e.g. centrifuges). In addition, cost and scalability of filtering tailings is one of the deterrents for mining companies. More research into decreasing costs and improving scalability (not just in processing, but during construction as well) of dewatering technologies would be beneficial.

Geochemistry

- There are unknowns around the effects of tailings ageing in conventional and dewatered facilities on permeability, geotechnical stability, saturation and ML, ML/ARD, etc. There are also unknowns around the effects of seepage chemistry on tailings in dewatered facilities. Further research and long-term monitoring of tailings facilities should be completed to better understand these effects and appropriately design for and manage them.
- More research would be beneficial on the use of amendments or compaction as a ML/ARD control (or permeability control). Compaction can minimize water and oxygen infiltration. The effectiveness of this strategy will likely be dependent on the tailings properties.

RÉSUMÉ

Introduction

Les parcs à résidus miniers présentent des risques tant physiques que géochimiques qui doivent être gérés tout au long de leur durée de vie, depuis leur conception et leur construction, jusqu'à la fermeture de la mine et au-delà. Au Canada, la plupart des mines gèrent leurs résidus sous la forme de boues accumulées derrière des digues de confinement (désignées dans le présent rapport par l'expression « installations classiques de résidus »). En raison des défaillances, mineures ou importantes, survenues ces derniers temps dans des parcs à résidus, les risques que représentent les installations classiques de résidus miniers sont étudiés de plus près. Bien qu'aucune cause fondamentale unique n'ait été déterminée pour toutes les défaillances des digues de parcs à résidus, on a constaté qu'un des facteurs communs pour les conséquences plus lourdes des défaillances était la façon dont l'eau était stockée et se comportait. L'industrie a donc commencé d'envisager d'autres solutions que les installations classiques de résidus, dont l'assèchement des résidus avant leur dépôt (p. ex., épaississement, mise en pâte, filtration) ainsi que différents types de dépôt (p. ex., dépôt en pente, en cône, « à sec »).

L'objectif de la gestion des résidus miniers est de stocker les résidus en toute sécurité et de réduire les risques, particulièrement à long terme. À cette fin, la fermeture « à sec » réduit considérablement le risque physique et doit être comparée aux risques géochimiques potentiels. La planification et la gestion des résidus devraient être axées sur le long terme après la fermeture, et il serait donc essentiel d'en tenir compte lors de l'évaluation des technologies et des types de dépôts envisagés.

L'intérêt dans les résidus asséchés repose sur le désir de réduire les risques physiques posés par les installations classiques de résidus. Bien que nous disposions déjà de la technologie nécessaire pour construire des digues sûres, l'industrie n'a pas été en mesure d'atteindre la cible « zéro défaillance ». À l'heure actuelle, produire des résidus en pâte et des résidus filtrés en vue de leur élimination est plus coûteux que de produire des résidus classiques, à moins que d'autres facteurs ne fassent augmenter les coûts : coût des digues, coût de l'eau, manque d'acceptation de la part des collectivités, ou le fait qu'il serait plus approprié de stocker les résidus sous terre.

La transformation des résidus de boues en pâte fait l'objet de travaux de recherche et est étudiée par l'industrie depuis plus d'une décennie, mais l'idée n'a pas encore été largement acceptée par les intéressés. Plus récemment, on s'est intéressé aux résidus filtrés : les coûts diminuent et on propose de construire des installations à grand débit. Grâce aux innovations dans ce domaine, l'option des résidus filtrés peut devenir de plus en plus attrayante et présenter moins de risque que les résidus classiques ou en pâte. Cependant, d'autres facteurs doivent être pris en compte lors du choix d'une stratégie de gestion des résidus miniers (p. ex., les conditions du site, les risques géochimiques, les risques à long terme inhérents à la fermeture, les impacts environnementaux et les impacts sociaux).

Le présent rapport décrit l'état actuel des pratiques dans l'industrie minière canadienne. Nous y examinons les technologies d'assèchement des résidus, la façon dont les résidus sont placés et gérés, et nous évaluons leur efficacité relative pour la gestion des risques physiques et géochimiques. Le rapport présente également les axes possibles de recherche et de développement. Le lecteur sera

ainsi en mesure de comprendre les avantages et les limites des technologies d'assèchement des résidus, les pratiques de dépôt et la façon dont ces choix s'appliquent à des sites et à des projets miniers particuliers par rapport aux pratiques classiques. Le rapport devrait aider au choix des technologies et stratégies à envisager pour un projet donné, compte tenu des conditions du site, des contraintes du projet (p. ex., le calendrier de production), des propriétés physiques des résidus (p. ex., leur granulométrie et leur plasticité) et des propriétés géochimiques [p. ex. le risque que les résidus génèrent la lixiviation des métaux (LM) ou le drainage rocheux acide (DRA)].

Une stratégie de gestion des résidus tient compte de nombreux aspects de leur élimination, notamment: le type de dépôts (technologies classiques, épaississement et mise en pâte, filtration), les technologies de gestion des résidus (ségrégation, co-élimination, remblayage en fosse ou sous terre, assèchement, épaississement et filtration, etc.); ainsi que les aspects opérationnels, environnementaux, socio-économiques et de fermeture. La présente étude se concentre sur les types d'installations de résidus et les technologies d'assèchement, et présente une évaluation des autres technologies de gestion des résidus et des types de dépôts par rapport aux installations classiques de gestion des résidus sous forme de boues.

Notre étude vise plusieurs objectifs précis : (1) présenter l'utilisation des technologies d'assèchement des résidus et des types d'installations associés pouvant remplacer les systèmes classiques au Canada (ou dans d'autres pays ayant un climat similaire); (2) évaluer l'applicabilité et l'efficacité des technologies de remplacement pour ce qui est de réduire les risques physiques et géochimiques par rapport aux installations classiques de gestion des résidus, et (3) déterminer les possibilités de recherche et de développement. Cette étude n'est pas exhaustive et n'évalue pas toutes les autres stratégies ou facteurs à prendre en compte pour la gestion des résidus ni tous les facteurs pertinents (p. ex., les facteurs sociaux), ni les divers types de digues et structures de rétention qui constituent également un élément clé des technologies et des approches de gestion des résidus.

Nous avons suivi l'approche suivante pour cette étude:

- Étape 1 – Déterminer l'état actuel de la pratique et quels sont les projets utilisant des technologies de remplacement au Canada, en effectuant une revue de la littérature et une recherche dans les bases de données et en recueillant de l'information grâce à un questionnaire envoyé à tous les sites miniers canadiens.
- Étape 2 – Évaluer les technologies de remplacement, comparaison des technologies et des coûts de gestion des résidus à l'aide de l'information compilée dans le cadre de la détermination de l'état actuel des pratiques et de l'information relatives aux études de cas fournie par certains sites miniers.
- Étape 3 – Évaluer l'applicabilité aux mines canadiennes et définir les lacunes dans les connaissances. Les leçons tirées des études de cas dans le contexte de l'exploitation minière au Canada ont été résumées et les lacunes en matière de connaissances ont été déterminées, en vue de recherches plus approfondies.

Assèchement des résidus et types d'installations

L'état des résidus asséchés couvre un continuum allant de boues fluides (comme l'eau) à épaisses (comme la mélasse), à des pâtes (comme du dentifrice) et des résidus filtrés (ayant la consistance d'un sol). L'état des résidus asséchés est habituellement défini en fonction de la teneur en solides (masse des solides par rapport à la masse totale du mélange solide/liquide) et de la contrainte de cisaillement (soit la résistance à l'écoulement, ou encore la pression appliquée qui doit être dépassée pour qu'un fluide s'écoule). Différents types de résidus asséchés sont stockés dans différents types de dépôts (classiques, épaissis à haute densité ou en pâte, filtrés).

Installations classiques de résidus

Les installations classiques de résidus comportent un système de transport, souvent sous forme de pipeline, qui achemine les boues épaissies ou non (généralement de 20 % à 40 % de solides en poids, et jusqu'à 60 %) de l'usine de traitement du minerai ou de l'épaississeur au parc à résidus. Les résidus sont déposés hydrauliquement, en vrac, derrière des digues de confinement. Les résidus sont déposés au-dessus ou au-dessous de l'eau et se dispersent généralement; les matériaux grossiers restant près du point de rejet, et les matériaux plus fins étant transportés plus loin du point de rejet. Cette ségrégation peut être tant un aspect avantageux que préjudiciable de la technique classique. L'eau libérée des boues est recueillie dans un bassin à la surface des résidus et a) elle s'évapore; b) elle est rejetée de l'installation ou c) elle est récupérée pour l'usine de traitement du minerai.

Environ 90 % des mines canadiennes gèrent leurs résidus sous forme de boues déposées dans des installations classiques.

Les digues peuvent être construites à partir de matériaux excavés localement, de stériles miniers, de résidus miniers ou d'une combinaison de ces matériaux.

Cette étude ne s'attarde pas à comparer les différents types de structures de confinement et de matériaux pour les installations classiques (p. ex., installations en amont, en aval, ou axiales, dépôts de sable provenant des cyclones ou dépôts de stériles). La conception des digues est un élément important de la gestion des risques associés aux parcs à résidus, et on doit également en tenir compte lors de la sélection d'une stratégie de gestion des résidus.

Installations de résidus épaissis à haute densité ou en pâte

Dans les installations de ce type, les résidus sont acheminés dans un pipeline sous forme de résidus épaissis à haute densité ou en pâte (généralement de 60 % à 75 % de solides en poids, avec des contraintes de cisaillement de 40 Pa à 200 Pa). En raison de ces contraintes de cisaillement élevées, il peut s'avérer nécessaire d'utiliser des pompes volumétriques. Les résidus sont déposés hydrauliquement, en vrac, étalés sur des pentes plus raides que les boues non épaissies (en théorie, les pentes peuvent atteindre 4 %, mais en pratique, les pentes raides ne sont atteintes que sur une courte distance, et elles sont souvent de moins de 2 %, globalement). Un des objectifs de la technique des résidus épaissis ou en pâte peut être de réduire ou d'éliminer la ségrégation associée au dépôt classique des boues.

Des digues sont toujours requises, mais elles peuvent être plus petites que dans les installations de résidus classiques si les pentes des berges peuvent être mises à profit. Les installations de résidus épaissis à haute densité ou en pâte sont généralement exploitées sans bassins ou avec des bassins minimes sur la surface des résidus. Comparativement aux installations classiques, les résidus libèrent moins d'eau à mesure qu'ils se consolident. Cette eau ainsi que les précipitations et les eaux de ruissellement s'accumulent dans les bassins sur la surface des résidus près de la digue ou sont dirigées vers des bassins collecteurs externes où elle peut être recyclée dans l'usine de traitement du minerai ou rejetée.

À l'instar des installations classiques, la conception des digues dans ces installations peut varier. Elle ne fait pas l'objet de la présente étude.

Il s'agit du type d'installation le moins utilisé au Canada. D'après nos recherches, la cohérence des résidus au fil du temps et l'impossibilité de réaliser des pentes raides sont les principales préoccupations concernant les résidus épaissis à haute densité ou en pâte.

Installations de résidus filtrés

Dans les installations de résidus filtrés, les résidus asséchés doivent être transportés par camion ou par convoyeur, car ils sont partiellement saturés et se comportent comme un sol plutôt qu'un fluide. Les résidus filtrés sont généralement asséchés à plus de 80 % de solides et sont souvent proches de leur teneur optimale en humidité (soit la teneur en humidité à laquelle la densité maximale peut être obtenue par compactage). Les résidus filtrés compactés sont habituellement utilisés pour le confinement structurel du parc à résidus. Les infiltrations et le ruissellement sont recueillis et gérés dans des bassins collecteurs externes.

Par le passé, ce type d'installation a peu été employé au Canada, probablement en raison des coûts longtemps élevés associés à cette méthode. Cependant, de plus en plus d'installations de résidus filtrés sont proposées et construites au Canada.

Comparaison et leçons générales tirées de la recherche

Quelques leçons générales tirées de la recherche et des études de cas réalisées dans le cadre de la première étape de cette étude sont résumées dans les tableaux 1 et 2.

Tableau 1 Facteurs à prendre en compte pour tous les types d'installations de résidus

Élément	Facteurs à prendre en compte
Technologie de ségrégation	La ségrégation des particules (p. ex., la flottation des sulfures) et la gestion séparée des résidus sulfurés du LM/DRA peuvent être bénéfiques sur le plan environnemental et économique, surtout si cette technologie est mise en œuvre dès le début de l'exploitation minière.
Gestion de l'eau	La gestion sûre de l'eau dans tous les parcs à résidus est une des conditions indispensables à la qualité de l'eau et la stabilité physique du parc. Les parcs à résidus ne devraient pas accumuler d'eau à long terme et devraient disposer des permis appropriés de rejet d'eau. Au besoin, elles devraient aussi avoir une usine de traitement pour permettre le rejet de l'eau. La conception du site, la zone de captage, la sélection de la technologie et la remise en état progressive sont également des points dont tenir compte pour gérer l'équilibre hydrique.

Élément	Facteurs à prendre en compte
Gestion de la poussière	La poussière est une préoccupation dans tous les parcs à résidus. Il est possible d'humecter continuellement la surface des résidus, épaissis ou non. La remise en état progressive des résidus filtrés offre la possibilité de réduire les surfaces exposées à la production potentielle de poussière, mais les zones qui ne peuvent pas être réhabilitées (p. ex., les grandes zones de dépôt actif créées lorsque des convoyeurs mobiles sont utilisés) peuvent nécessiter une gestion active de la poussière.
Mise en dépôt	La mise en place de résidus dans des fosses à ciel ouvert « épuisées » et dans les galeries souterraines peut être une bonne approche pour la réduction des risques, tant géotechniques que géochimiques, liés aux résidus.
Risque et conséquence d'une défaillance	Le risque est le principal facteur à prendre en compte pour la conception, la construction et l'exploitation d'un parc à résidus. Les parcs à résidus devraient être conçues de façon à minimiser autant que possible les conséquences d'une éventuelle défaillance. Par exemple, on peut tout simplement décider de ne pas utiliser le parc à résidus pour le stockage à long terme de l'eau de la mine.
Fermeture	Les parcs à résidus devraient être conçues en vue d'une fermeture à sec prévoyant une utilisation appropriée des terrains et de l'eau, ou une modification du relief. Le coût du risque potentiel associé au parc à résidus pendant la fermeture à long terme devrait être pris en compte dans le processus de sélection du mode de fermeture.
Risques et coûts du cycle de vie	Lors de la planification de la gestion des résidus, il faut tenir compte du profil de risque complet des stratégies de gestion des résidus de remplacement (y compris les coûts du cycle de vie). Cela peut se faire au moyen d'une évaluation structurée, telle qu'une l'analyse Failure Modes and Effects Assessment (FMEA).

Tableau 2 Principaux facteurs à prendre en compte pour les différents types d'installations

Élément	Installations classiques de résidus	Installations de résidus épaissis à haute densité ou en pâte	Installations de résidus filtrés
Avantages	▪ Technique largement applicable à différents types de résidus. Les processus sont bien connus. ▪ Les résidus, à une profondeur de 10 m à 20 m une fois mis en dépôt, se consolident naturellement à la densité *in situ*, sous forme de résidus épaissis à haute densité ou en pâte. ▪ Offre une plus grande souplesse opérationnelle pour la gestion globale de l'eau en raison de la capacité d'atténuation sur la surface des résidus (y compris la variabilité saisonnière). ▪ Peut fournir des conditions saturées pour la gestion des résidus potentiellement acidogènes. ▪ Si on conçoit correctement ce genre d'installation, on peut en assurer la fermeture à l'état « sec ».	▪ Plus grande récupération d'eau pendant le traitement; moins d'eau à gérer dans le parc à résidus. ▪ Il n'y aura pas nécessairement de ségrégation, ce qui produirait un résidu ayant une conductivité hydraulique potentiellement faible et une capacité élevée de rétention d'humidité (peut être utilisé pour contrôler le LM/DRA). Remarque : la cohérence des résidus dépendra de la variabilité de leurs propriétés. ▪ Les résidus en pâte peuvent être utilisés comme remblai souterrain, le cas échéant. ▪ Si on conçoit correctement ce genre d'installation, on peut en assurer la fermeture à l'état « sec » plus facilement que pour une installation classique de résidus. ▪ Une défaillance, le cas échéant, se manifesterait probablement par un affaissement local et les conséquences se limiteraient à la zone locale (ou sur une distance équivalant à environ 20 fois la hauteur[2]) à moins que le matériau ne s'effondre dans un plan d'eau.	▪ Peut permettre le stockage dans des zones à forte pente, dans des endroits où il y a des restrictions d'espace ou dans d'autres circonstances où une installation classique de résidus n'est pas pratique. ▪ Une récupération maximale de l'eau pendant le traitement est avantageuse dans les régions où l'eau est rare. ▪ Offre plus de flexibilité pour la stratégie de placement et la configuration finale, ce qui peut permettre une réhabilitation progressive. ▪ Méthode se prêtant bien à la fermeture à l'état sec et à la mise en place d'un relief. ▪ Une défaillance, le cas échéant, se manifesterait probablement par un affaissement local et les conséquences seraient limitées à la zone locale (ou sur une distance équivalant à environ 10 fois la hauteur[1]) à moins que le matériau ne s'effondre dans un plan d'eau.
Limites	▪ Toutes les installations classiques ne sont pas conçues de la même façon et, par conséquent, il y a une gamme de risques associés à ces installations. ▪ Bien que les défaillances soient rares, les conséquences d'une défaillance peuvent être importantes. Un effort important de gestion et de conception	▪ Les épaississeurs et les filtres à haute densité nécessitent une attention opérationnelle et sont sujets à des « perturbations » du système causées par la variabilité, la granulométrie ou les erreurs de l'opérateur. ▪ On peut passer des mois ou des années à optimiser le système d'épaississement avant qu'il ne produise un résidu consistant, et la teneur en	▪ Peut ne pas être applicable à tous les types de résidus dans toutes les situations (les résidus à forte teneur en particules d'argile sont plus difficiles à filtrer pour obtenir le degré d'humidité requis). ▪ Les filtres ou les usines de filtration nécessitent une attention opérationnelle accrue et sont sujets à des

[2] L'estimation de la distance de glissement est présentée uniquement aux fins de comparaison.

Élément	Installations classiques de résidus	Installations de résidus épaissis à haute densité ou en pâte	Installations de résidus filtrés
	est nécessaire pendant la longue durée de vie opérationnelle du parc pour réduire les risques à un niveau acceptable. ▪ Les risques associés aux digues construites en amont peuvent être sous-estimés et le faible coût de ces structures peut dominer le processus de décision. ▪ La gestion de l'eau doit être équilibrée afin d'éviter de stocker trop d'eau dans le parc, tout en permettant un stockage d'urgence, des périodes d'arrêt, l'acheminement de l'eau excédentaire du site dans les résidus, et d'autres perturbations du système. La gestion de l'eau pendant la longue durée de vie de ces structures peut être difficile et les perturbations qui causent des niveaux élevés dans les bassins sur la surface des résidus constituent un important facteur de risque pour les installations classiques. ▪ La ségrégation des résidus peut causer un problème de production d'acide dans les sables de plage ou de consolidation lente des zones boueuses.	solides obtenue est souvent inférieure d'au moins 5 % à l'objectif de conception. ▪ Des pompes volumétriques peuvent être nécessaires pour le transport des résidus, et elles sont plus coûteuses et plus difficiles à utiliser. ▪ Les pentes des digues sont difficiles à prédire et varient selon les pratiques d'exploitation, les propriétés des résidus et les conditions météorologiques. ▪ Il est souvent difficile d'avoir un temps de séchage suffisant (qui peut être requis pour assurer la stabilité) dans les climats humides, et le parc à résidus peut alors nécessiter une grande zone de séchage et une rotation des points de rejet. ▪ Habituellement, le parc à résidus ne fournit pas un stockage adéquat pour atténuer les débits d'eau saisonniers. Par conséquent, un stockage d'eau externe est nécessaire pour gérer efficacement le ruissellement et les autres eaux sur le site. ▪ Les précipitations et le vent sur les pentes peuvent accroître l'érosion. ▪ Il y a peu ou pas de précédents pour ce qui est de la fermeture de ce type d'installation.	« perturbations » du système dues à la variabilité du minerai, à la granulométrie ou à l'attention de l'opérateur. Des bassins de stockage supplémentaires sont nécessaires en cas de perturbation du système nécessitant l'arrêt de la filtration. ▪ La traficabilité des résidus filtrés peut représenter un défi, selon la teneur en humidité des résidus provenant de l'usine de filtration et les conditions climatiques. ▪ La mise en place est plus difficile dans les climats froids et humides. L'utilisation de hangars pour stocker temporairement les résidus est généralement nécessaire par temps humide lorsque la mise en place doit cesser. ▪ La mise en place par convoyeur ou par camion et pelle peut être difficile à adapter lorsque les volumes sont importants. ▪ Il faut encore employer des « zones structurales » (qui font office de digues), faites de résidus compactés pour le confinement. ▪ Nécessite un stockage externe de l'eau pour gérer les eaux de ruissellement et les autres eaux sur le site. ▪ Les précipitations et le vent sur les pentes peuvent accroître l'érosion. Cependant, certaines installations de résidus filtrés peuvent être disposées de façon à assurer une réhabilitation progressive, ce qui aidera à contrôler l'érosion. ▪ Plus grande consommation d'énergie.

Élément	Installations classiques de résidus	Installations de résidus épaissis à haute densité ou en pâte	Installations de résidus filtrés
			▪ Difficulté de gérer les produits sulfurés du LM/DRA et LM par des mesures de contrôle à la source en raison de la faible saturation des matériaux. ▪ Aucun précédent de fermeture, mais peut permettre une réhabilitation progressive.
Risque physique	▪ **Maximal pendant l'exploitation.** ▪ La présence du bassin d'eau sur la surface des résidus pendant l'exploitation augmente les conséquences et la probabilité d'une défaillance. ▪ Les résidus lâches et saturés peuvent devenir mobiles, surtout si l'eau du bassin est libérée en raison d'une défaillance.	▪ **Maximal pendant l'exploitation et la fermeture.** ▪ Nécessite toujours une certaine gestion de l'eau sur la surface des résidus. ▪ Les résidus (non compactés) ont un potentiel de mobilité et ne sont pas entièrement confinés par une digue en cas de défaillance structurale. ▪ Peu de précédents pour l'exploitation à grande échelle.	▪ Il peut s'avérer difficile de toujours respecter les spécifications des matériaux pendant la construction, ce qui augmente la probabilité de défaillance des pentes. ▪ Aucun précédent pour l'exploitation à grande échelle.
Risque géochimique	▪ **Maximal pendant l'exploitation et la fermeture.** ▪ Lorsque les résidus sont sulfurés, l'oxydation et le ruissellement ou l'infiltration à travers ces zones perméables peuvent causer le LM ou LM/DRA. Cependant, il existe des études de cas comparatives (précédents) de gestion réussie pour le LM ou LM/DRA. ▪ Dans de bonnes conditions climatiques, la possibilité de saturer les résidus pour gérer le DRA est un des principaux avantages de cette méthode d'élimination. Cependant, si les résidus ne sont pas gérés correctement, et qu'il y a un LM ou LM/DRA, une gestion plus serrée de l'eau sera nécessaire.	▪ **Maximal pendant l'exploitation et la fermeture.** ▪ Les exploitations à petite échelle peuvent être couronnées de succès et contrôler les processus LM/DRA sans avoir un bassin d'accumulation d'eau à la surface des résidus, mais les exploitations à grande échelle présentent un risque plus élevé de LM/DRA par rapport aux installations classiques de résidus.	▪ **Maximal pendant l'exploitation.** ▪ Les résidus partiellement saturés contenant des sulfures vont s'oxyder et générer des processus LM/DRA. Cependant, un compactage efficace, un aménagement rationnel et une réhabilitation progressive (si possible) peuvent aider à contrôler le LM/DRA et à limiter la gestion active de l'eau. ▪ Les installations à grande échelle présentent un risque plus élevé de LM/DRA par rapport aux installations à petite échelle ou aux installations classiques de résidus en raison des méthodes de mise en place.

Élément	Installations classiques de résidus	Installations de résidus épaissis à haute densité ou en pâte	Installations de résidus filtrés
Coûts	▪ C'est habituellement l'option nécessitant les coûts d'immobilisation et d'exploitation les plus faibles. ▪ En cas de LM ou de DRA, les coûts de gestion de l'eau peuvent devenir prohibitifs avec le temps. ▪ Les coûts totaux du cycle de vie peuvent être importants si la fermeture prend du temps et si une gestion active de l'eau à long terme est nécessaire. ▪ Le coût d'une défaillance pourrait être immense.	▪ Les coûts d'immobilisation et d'exploitation sont habituellement plus élevés que pour une installation classique de gestion des résidus. ▪ En cas de LM ou de DRA, les coûts de gestion de l'eau peuvent devenir immenses avec le temps. ▪ Les coûts totaux du cycle de vie peuvent être importants si la fermeture prend du temps et si une gestion active de l'eau à long terme est nécessaire. ▪ Le coût d'une défaillance pourrait être important, en particulier si une grande installation a une défaillance causer par la liquéfaction. Cependant, il n'y a que quelques grandes installations de ce type dans le monde et on ne connaît aucun précédent de défaillance ayant entraîné des conséquences extrêmes.	▪ C'est habituellement l'option nécessitant les coûts d'immobilisation et d'exploitation les plus importants. ▪ En cas de LM ou de DRA, les coûts de gestion de l'eau peuvent devenir prohibitifs avec le temps s'ils ne sont pas progressivement réhabilité. ▪ L'installation devrait pouvoir être fermée assez rapidement. ▪ Le coût d'une défaillance devrait être inférieur à celui des autres types d'installations.

Lacunes dans les connaissances et recommandations pour une étude plus poussée

En général, les principales lacunes dans les connaissances sont dues au manque de partage des informations et des leçons apprises, y compris les échecs ou les erreurs qui sont des éléments essentiels de l'apprentissage. Nous avons divisé les principales lacunes dans les connaissances et les recommandations en vue d'une étude plus approfondie en quatre catégories : les coûts, la fermeture, les autres technologies, la géochimie.

Coûts

- Il y a un manque d'information publique sur le coût de la gestion des résidus miniers – de la construction à la fermeture et la post-fermeture. La compilation d'une base de données structurée sur les coûts aiderait à faire connaître le coût du cycle de vie de la gestion des résidus et contribuerait à la prise de décisions futures en matière de gestion des résidus.
- Les coûts liés au cycle de vie des parcs à résidus miniers portent généralement sur la construction, l'exploitation, la fermeture et la post-fermeture. Cependant, au stade de la planification, il arrive souvent que les plans de fermeture ne soient pas complètement élaborés et les exigences de fermeture peuvent changer pendant la durée de vie de la mine. De plus, il arrive que, lors de la comparaison des différents scénarios de conception et de fermeture, le profil de risque potentiel de chaque solution de remplacement ne soit pas expressément présenté. Il serait utile d'élaborer un profil de risque structuré pour les méthodes de remplacement de gestions des résidus afin de déterminer les risques acceptables et inacceptables et de prendre une décision quant à la stratégie de gestion à adopter.

Fermeture

- Il serait également avantageux de compiler des études de cas de fermeture pour tous les types d'installations de résidus. Le rendement et le suivi des couvertures sèches sont très importants dans la gestion géochimique, le but étant de fermer les installations sans une accumulation d'eau a la surface des résidus.
- Un objectif important, pour les parcs à résidus miniers, est que l'installation puisse être transformée, au fil du temps, en un relief naturel ou en un site d'utilisation durable des terres et des eaux. Il y a lieu d'approfondir les recherches sur les caractéristiques qui pourraient être requises ou incorporées dans la conception du parc, afin qu'elle puisse éventuellement être classée comme relief s'intégrant au paysage environnant. On devrait également définir les critères permettant de définir un relief.
- Il serait aussi avantageux d'effectuer des recherches sur la mobilité potentielle à long terme des résidus, ce qui aiderait les planificateurs à comprendre les risques à long terme et à concevoir des installations permettant de minimiser ces risques.

Autres technologies

- La flottation des sulfures peut aider à gérer les risques géochimiques en réduisant la teneur en sulfures de la plupart des résidus et en permettant une gestion séparée du volume moindre de sulfures concentrés. De nouveau, il serait avantageux de poursuivre les recherches sur d'autres méthodes de traitement visant à réduire la concentration des métaux et contaminants préoccupants dans les résidus.

- Des technologies non classiques d'assèchement font l'objet de recherches, mais ne sont pas utilisées commercialement en raison de leurs coûts (p. ex., utilisation de centrifugeuses). De plus, le coût de la filtration des résidus et de la mise à l'échelle industrielle de cette technique est l'un des éléments dissuasifs pour les sociétés minières. Il y a lieu de poursuivre les recherches sur la réduction des coûts et l'amélioration de la mise à l'échelle industrielle (pas seulement pendant le traitement, mais aussi pendant la construction) des technologies d'assèchement.

Géochimie

- Il subsiste des inconnues concernant les effets d'altération des résidus dans les parcs – classiques et avec résidus asséchés – sur la perméabilité, la stabilité géotechnique, la saturation, le LM/DRA, etc. On ignore également les effets de la chimie des suintements sur les résidus dans les installations avec résidus asséchés. Des recherches supplémentaires et le suivi à long terme des parcs à résidus miniers devraient être réalisées afin que l'on puisse mieux comprendre ces effets, et concevoir et gérer les installations en conséquence.
- Il y a lieu d'effectuer des recherches sur l'utilisation d'amendements ou du compactage pour contrôler les processus LM/DRA ou la perméabilité. Le compactage peut minimiser l'infiltration d'eau et d'oxygène. L'efficacité de cette stratégie dépendra probablement des propriétés des résidus.

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ARD	Acid Rock Drainage
ART	Altered Rock Tailings
BOD	Biochemical Oxygen Demand
CAPEX	Capital Expenditure
CDA	Canadian Dam Association
CIP	Carbon-in-Pulp
COD	Chemical Oxygen Demand
CPK	Coarse Processed Kimberlite
CT	Coarse Tailings
FPK	Fine Processed Kimberlite
FT	Fine Tailings
GARD	Global Acid Rock Drainage
HRT	Hard Rock Tailings
ICOLD	International Commission on Large Dams
INAP	International Network for Acid Prevention
KCB	Klohn Crippen Berger
MAAT	Mean Annual Air Temperature
MAC	Mining Association of Canada
MEND	Mine Environment Neutral Drainage
MFT	Mature Fine Tailings
ML	Metal Leaching
MMER	Metal Mining Effluent Regulation
NMD	Neutral Mine Drainage
NP	Neutralization Potential
NPAG	Not Potentially Acid Generating
OPEX	Operational Expenditures
PAG	Potentially Acid Generating
PMF	Probably Maximum Flood
PSD	Particle Size Distribution
SD	Saline (Mine) Drainage
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
UFT	Ultra Fine Tailings
USCOLD	United States Committee on Large Dams

GLOSSARY OF TERMS

Acid Rock Drainage (ARD)	Acidic drainage that occurs when minerals are exposed to weathering effects of oxygen, water and sulphide-oxidizing bacteria.
Altered Rock Tailings (ART)	Tailings that are sandy silt, with trace to some clay-sized particles, and have low plasticity.
Atterberg Limits	Water content boundaries between the states of consistency of a soil (e.g. liquid limit and plastic limit).
Beach	The portion of tailings in an impoundment that is not submerged below the reclaim pond.
Beach Slope	The grade or steepness of the surface of tailings above water.
Bleed Water	The water released after the tailings slurry is deposited.
Borrow Material	Material sourced from outside of an excavated area for use in construction.
Centreline Construction	A tailings dam construction method in which the centreline of the dam is raised vertically and does not shift upstream or downstream during subsequent raises. Typically, structure fill is placed on the downstream side of the centreline and the upstream side of the core is supported by fill or tailings that slopes downwards towards the tailings surface.
Centrifugal Pump	A pump that uses centrifugal force (impellers on a rotational axis) to transport tailings slurry.
Clay-sized Particle	Grain size is classified as clay if the particle diameter is <0.002 mm.
Coarse Tailings (CT)	Tailings that are silt and sand, non-plastic. See *plasticity*
Co-disposal	Storage of tailings and waste rock together with some degree of co-mingling. May also be referred to as co-deposition or co-placement.
Confining Stress	The combined hydrostatic and lithostatic stress; i.e. the total weight of above a specific depth.
Consolidation Water	The water released as the tailings mass increases in density under self-weight.
Contact Water	Water that has come in contact with components or products of the mining operation.
Conventional Tailings	Tailings directly from the ore processing facility, with no additional dewatering, stored behind containment dams or dykes. Solids contents range from 20% to 40%. The most widely practiced tailings deposition technique in Canada. Also termed *conventional slurry*.
Cover	A layer of material placed over deposited tailings, usually for closure of a facility.
Critical State Line	The relationship of void ratio-effective stress conditions achieved after shearing a soil to large displacement and after all net void ratio changes and effective stress changes are complete.
Cyclone Underflow	The heavier, coarser and free draining sand that is produced at the apex of a cyclone (see *cycloned sand*).
Cycloned Sand	The coarse fraction (see *cyclone underflow*) of tailings that has been separated from the fine fraction by a hydrocyclone.
Deep Cone Thickener	A design of thickener with the highest depth-to-diameter ratio and a deeper solids bed than *high rate/high capacity thickeners*. This type of thickener has a steeply sloping floor. This design results in higher compression of the underflow, which is output as a non-Newtonian and non-segregating paste of up to 70% solids content. See *thickeners*.
Desiccation	When tailings are dried to a state that the soil structure contracts and causes cracks in the surface.
Dewatering	Process in which the percentage of water in the tailings slurry is reduced.

Downstream Construction	A method of dam construction in which the centreline of the dam is shifted downstream with subsequent raises, resulting in a core inclined in the downstream direction. This method requires that structural fill be placed in the downstream shell during raising to support the inclined core.
Drain-down	The downward movement of the phreatic surface in a tailings facility over time.
Evapotranspiration	The loss of water by both *evaporation* and *transpiration*.
Evaporation	The transfer of water from open water surfaces to the air.
Filter (*dewatering* equipment)	A piece of equipment that removes water from a slurry by forcing the water through a membrane that does not allow solids to pass through it.
Filtered Tailings	Tailings dewatered such that they behave like a soil; solids content of 75% to 90%; achieved by thickening followed by vacuum or pressure filtration; stored in piles; also known as dry stack.
Fine Tailings (FT)	Tailings that are silty, may contain some clay-sized particles; low to moderate plasticity. See *plasticity*.
Flocculant	A chemical added to a slurry that enhances the rate of settling of solids in a clarifier or thickener by promoting the growth of flocs (clumps of solids), which settle more rapidly than individual particles.
Glaciolacustrine	Soils formed in a lake bottom from sediments deposited by glacial meltwater.
Gradation	Classification of a material based on the particle size. Also see *particle size distribution*.
High Capacity Thickener	A design of thickener that relies on the use of *flocculants*, the base slope, and optimization of the flux-concentration relationship (relationship between the feed solids content, settling flux, and flocculant dosage) to improve throughput. See *"thickener"*.
High Compression Thickener	A design of thickener that produces underflow with a high yield stress and high solids content. Once placed, the slurry from this thickener should have non-segregating behaviour and release minimal water.
High-Density Thickened	Output from high compression thickeners. Also see *high compression thickener*.
High-Density Thickener	See *high compression thickener*.
High Rate Thickener	See *High capacity thickener*.
Hydraulic Conductivity	A measure of how quickly water moves through rock, soils, and tailings under a pressure difference.
Hydro-cycloning (Cycloning)	Processing tailings using a cyclone which separates finer material (overflow) from the coarser material (underflow) by centrifugal force.
In-pit Tailings Deposition	Storage of tailings in an existing open pit, or portion of.
In-situ	In place. In tailings context, it refers to tailings in a facility. For example, in-situ density is the density of the tailings within the facility.
Landform	A designated structure considered to have a risk profile similar to the surrounding environment. – Health Safety and Reclamation Code for Mines in British Columbia (MEM 2016)
Liquefaction (Seismic and Static)	Process by which saturated, loose sediments lose strength due to increased pore water pressure and behave like a fluid. *Seismic* liquefaction occurs due to an earthquake. *Static* liquefaction occurs due to other triggers (for example: high rates of rise, poor drainage, etc.).
Low Reactivity Tailings	Tailings where *acid rock drainage* and *metal leaching* are not expected to occur at concentrations above water quality guidelines. These tailings generally do not require special management or considerations for water quality impacts outside of *total suspended solids* controls.

Mature Fine Tailings (MFT)	*Ultra-fine tailings* found in the oil sands that are produced as a result of using hot or warm water to extract bitumen from sand.
Metal Leaching (ML)	Oxidation of sulphide minerals or the dissolution and weathering of minerals that leads to the release of metal(loid)s leading to concentrations in seepage and effluent above the water quality guidelines.
Moisture Content	The ratio of water to tailings solids by weight.
Neutral Mine Drainage (NMD)	Neutral pH drainage resulting from the natural oxidation of base minerals when exposed to air and water; contains heavy metals and less sulphate than *saline drainage*.
Neutralization Potential (NP)	The amount of acid able to be neutralized, typically reported in mg/L of $CaCO_3$ (calcium carbonate).
Neutralization Potential Ratio (NPR)	The ratio of Neutralization Potential (NP) to Acid Potential (AP). Theoretically, tailings are not-Potentially Acid Generating (NPAG) for NPR above 2, Potentially Acid Generating (PAG) for NPR below 1, and Uncertain if NPR is between 1 and 2 (INAP 2009).
Newtonian Fluid	A fluid whose *viscosity* remains constant when stress is applied; water, for example. A non-Newtonian fluid's viscosity changes when stress is applied; toothpaste, for example.
Non-Sulphidic Leaching	The leaching of metal(loid)s and non-metals at concentrations above water quality guidelines from rock and tailings that are not a result of sulphide oxidation (See Potentially Acid Generating) but result from mineral weathering and dissolution. The material could be classified as Not Potentially Acid Generating.
Normally Consolidated	A soil which is experiencing it's highest applied stress (load).
Not Potentially Acid Generating (NPAG)	Tailings with qualities that prevent them from producing acid. A NPR above 2 (INAP 2009). These include some sulphidic leaching tailings, non-sulphidic leaching tailings, and *low reactivity tailings*.
Optimum Moisture Content	The *moisture content* at which the maximum density can be achieved through compaction and estimated with a Proctor compaction test.
Ore Processing Facility	The process plant in which ore is milled, and metal concentrate and tailings are produced.
Overconsolidated	A soil which has had stress (load) removed.
Overtopping	A type of dam failure in which the level of the pond rises above the crest of the dam resulting in flow over the dam and release of tailings and/or water.
Oxidation	The process in which a substance loses one or more electrons when it reacts with oxygen. Oxidation is part of the process of ARD, resulting in the formation of acidic water.
Partially-saturated	Less than 100% saturation
Particle Size Distribution (PSD)	Relative proportions of differently sized particles in a granular material.
Paste Tailings	Definitions vary; widely accepted definitions include: ▪ Tailings dewatered such that they will "bleed" limited volumes of excess water. This is similar to the initial settled density which can be derived from "jar" settling tests in the laboratory. ▪ Tailings dewatered such that the yield stress is approximately 200 Pa and positive displacement pumps (as opposed to centrifugal force pumps) are required for transport. ▪ Tailings dewatered such that a slump of 150 mm to 250 mm is achieved in a concrete slump test.
Peak Strength	The peak strength of a soil during shearing.
Phreatic Surface	The line of zero pressure within an embankment or foundation. Commonly referred to as the *water table*.

Plasticity	Quality of being easily shaped or molded, as quantified by the *Atterberg Limits*; *high plasticity tailings.*
Pore Pressure	Pressure within the water that is contained within a soil's void space.
Pore Water	Water contained within a soil's void space.
Positive Displacement Pump	A pump that moves a fluid, slurry or paste by forcing (displacing) a fixed volume of the substance into the discharge pipe with each pump cycle.
Potentially Acid Generating (PAG)	Tailings with qualities that could cause them to produce acid. A NPR less than 1 (INAP 2009).
Process Water	Water used in a mine's *ore processing facility*; usually recycled back to the plant.
Reagent	A substance added to a system to cause a chemical reaction.
Residual Strength	The strength of a soil during shearing after peak strength is reached.
Rheology	The study of how substances (such as liquids, slurries or pastes) deform and flow; defined by a combination of *viscosity* and yield stress.
Risk	A measure of the hazard posed by a potential event considering both its Likelihood and Consequence.
Saline Drainage (SD)	Neutral drainage resulting from the natural oxidation of base minerals when exposed to air and water; contains more sulphate than *neutral mine drainage*.
Segregation	The separation of particles based on a property (specific gravity, grain size, for example).
Seismic	As it relates to stability: dynamic or cyclic stress conditions.
Slump (concrete slump test)	A measure of the vertical distance that a material subsides due to gravity.
Slump (slope failure)	A type of slope failure when a mass of a slope slides a relatively short distance down the slope.
Slurry	A mixture of tailings solids and water that behaves like a liquid.
Solids Content	The ratio of the weight of solids in slurry to the total slurry weight.
Specific Gravity	The ratio of the solids or slurry density to the density of water.
Static	As it relates to stability: unchanging or static stress conditions.
Strain	The movement of a soil under stress.
Strip Ratio	Ratio of the volume of overburden (waste rock) to the amount of ore (material that is processed in the *ore processing facility*) extracted for a mine.
Structural Zone	A zone within a dam or *filtered tailings* pile that provides structural support against slope failure.
Sub-aqueous Tailings Deposition	Depositing tailings within a water body, either constructed or natural.
Sulphides	A type of mineral rich rock that contains oxygen-free compounds of sulphur.
Surface Disposal	Disposal of tailings in a tailings facility located above ground.
Tailings	The remaining portion of processed ore after the valuable fraction of metals or minerals have been separated in the *ore processing facility*. One of the primary waste products of mining.
Tailings Facility	A constructed facility that is used to store tailings. Conventional facilities typically consist of one or more embankment dams used for tailings and reclaim pond retention.
Thickened Tailings	Tailings dewatered to a *solids content* of 50% to 65% through use of thickening equipment; typically stored behind containment dams or dykes.
Thickener	A device for separating solids from liquid by sedimentation. The inflow is injected into a large, round basin. Solids thicken as they settle to the bottom with gravity. The *underflow* is released from the bottom and is a mixture of solids and water (it has a higher *solids content* than the inflow). The *overflow* is the extracted water and generally spills from the top of the basin.
Total Dissolved Solids (TDS)	Solids including any minerals, salts, metals, cations or anions that are dissolved in water.

Total Suspended Solids (TSS)	Solids including any minerals, salts, metals, cations or anions that are suspended in water.
Transpiration	The process in which plants absorb water through their roots and then release water vapor to the atmosphere through their leaves.
Ultra-Fine Tailings (UFT)	Tailings that are silty clay, high plasticity, very low density and with very low *hydraulic conductivity*.
Underground Disposal	Disposal of tailings below ground, typically within portions of a mine's underground workings that are no longer active or required.
Undrained Loading	When the rate loading is greater than the rate at which pore water pressures, that are generated due to the action of shearing the soil, may dissipate.
Upstream Construction	A method of dam construction in which the centreline is translated upstream, over the tailings *beach*, with subsequent raises. This method requires that material placed in the upstream direction is well-drained and compacted, or that it naturally settles to an adequate density.
Varve	A layer in a soil unit that represents a year of deposition. Varves are commonly seen in lacustrine deposits, where coarser particles are deposited during the high-energy spring and summer months and finer particles are deposited during the low-energy fall and winter months.
Viscosity	The measure of a fluid's resistance to flow. For example, water has a lower viscosity than paste.
Water Balance	A framework that describes the contributors to water flows into and out of a closed system. This will indicate if the total amount of water in the system is increasing (surplus), decreasing (deficit) or remaining neutral.
Water Content	See *moisture content*.
Yield Stress/Shear Yield Stress, Yield Strength	The applied stress that must be exceeded in order to make a fluid flow.

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1 INTRODUCTION

1.1 General

Facilities built to store mine *tailings* pose both physical and geochemical risks that must be managed throughout the life of the facility, from design and construction, through to the closure of the mine and beyond. In Canada, most mines manage their tailings as a *slurry* deposited behind containment dams (designated in this report as "*conventional tailings* facilities"). In the wake of small and large-scale *tailings facility* failures, the risks posed by conventional tailings facilities are increasingly being scrutinized. Although one root cause has not been identified for all tailings dam failures, a common contributing factor includes the storage and behaviour of water within the facilities. This has led the industry to reconsider alternatives to conventional tailings facilities, including *dewatering* tailings prior to deposition (e.g. thickened, paste and filtered) as well as different facility types (e.g. downslope, cone, and stack/pile).

Driving the interest in dewatered tailings is a desire to reduce the physical risk posed by conventional tailings facilities. Although the technology exists to build safe dams, the industry has not been able to achieve zero failures. Currently, creating paste and *filtered tailings* for disposal is more costly than conventional tailings, unless other factors are important cost drivers: dam cost, water cost, a lack of community acceptance, or the fact tailings would be better stored underground.

Turning slurry tailings into paste has been an industry and research focus for more than a decade, but it has not achieved broad acceptance in the industry. More recently, interest has moved towards filtered tailings; costs are decreasing and larger throughput plants are being proposed. These innovations may make filtered tailings an increasingly attractive, lower-physical-risk option compared to conventional or paste tailings. However, other factors need to be considered when selecting a tailings management strategy (e.g. site conditions, geochemical risks, long-term closure risks, environmental impacts and social impacts).

This report presents a snapshot of the current state-of-practice in the Canadian mining industry. It looks at the technologies used to dewater tailings, how tailings are placed and managed, and evaluates their relative efficacy in addressing physical and geochemical risks. It also identifies opportunities for further research and development. The reader should gain an understanding of the strengths and limitations of tailings dewatering technologies, deposition practices, and how these choices apply to specific sites and mining projects compared to conventional practices. The report should help guide which technologies and strategies should be considered for a project, taking into account site conditions, project constraints (e.g. production schedule), tailings' physical properties (e.g. grain-size, and plasticity), and geochemical properties (e.g. the potential for tailings to generate *metal leaching* (ML) and/or *acid rock drainage* (ARD)). More importantly, the reader should understand there is not a one-size-fits-all solution to tailings management.

Every project and tailings facility has a unique combination of site conditions, tailings characteristics, available resources, social and regulatory environment, and countless other factors that must be considered throughout the project life-cycle. Many of the observations and conclusions in this report are generalized and there are undoubtedly exceptions to some of these statements depending on project-specific conditions.

This study does not delve into comparing the different types of containment structures and material types for conventional facilities (e.g. upstream, downstream, centreline, *cycloned sand*, waste rock). Containment dam design is an important part of risk management associated with tailings facilities that should also be considered during selection of a tailings management strategy.

1.2 Objective

Klohn Crippen Berger (KCB) was commissioned by the Mine Environment Neutral Drainage (MEND) Project Secretariat to undertake this state-of-practice assessment of tailings management technologies in Canada. Following a detailed examination of the alternatives to conventional slurry for the management of tailings (e.g. thickened, paste and filtered tailings), the objective of the study is to document the strengths, limitations, and physical and geochemical risks of these alternative technologies and compare them to those of conventional slurry. Strengths, limitations and risk are to be considered across the entire life-cycle of tailings facilities, from design and construction to the long-term post-closure period.

Where knowledge gaps are identified, recommendations for further work are provided. For example, MEND requested that KCB *compare the relative costs of these technologies and practices across the entire life-cycle, including construction and operational costs, closure and long-term (post-closure) costs*, but due to limited availability of costing information, particularly on closure and post-closure costs, a recommendation is made to collect additional cost information.

1.3 Approach

The following approach was taken to provide the information and tools to evaluate alternative tailings management technologies in Canada:

- **Step 1 - Identify the Current State-of-Practice in Canada**

  The first step in this assessment was to identify how tailings at Canadian mines are managed.

  - **Step 1a - Case History Review of Tailings Technologies and Practices**

    An inventory of Canadian mining projects and international tailings facilities identified mine sites that use alternatives to conventional slurry.

    A questionnaire was sent to Canadian mine sites requesting information on site characterization, tailings properties, tailings technologies, commodity type, location, production rate, etc. Information for projects identified as using alternatives to conventional slurry technology was supplemented by literature searches and direct contact with mine personnel.

  - **Step 1b - Tailings Characterization**

    Following a review of the most commonly produced tailings types, the process technologies were screened based on physical and geochemical tailings types.

- **Step 1c - Overview of Tailings Processing Technologies**

  Tailings processing technologies were reviewed and summarized, with a focus on dewatering technologies.

- **Step 2 - Evaluation of the Alternatives**

  - **Step 2a - Comparison of Tailings Management Technologies**

    Tailings management alternatives were evaluated based on the identification of the current state-of-practice and the case study information.

  - **Step 2b - Cost Comparison of Tailings Management Technologies**

    As part of the evaluation of alternatives, the comparative cost of processing and transporting materials produced by different dewatering technologies was assessed. Discussion on life-cycle costs is included, however, a lack of information and project-specific constraints prohibited inclusion of these costs in the comparison assessment.

- **Step 3 - Application to Canadian Mines and Knowledge Gaps**

  Lessons learned from the case histories in the context of mining in Canada were summarized and knowledge gaps identified for further research.

1.4 Focus and Limitations of Study

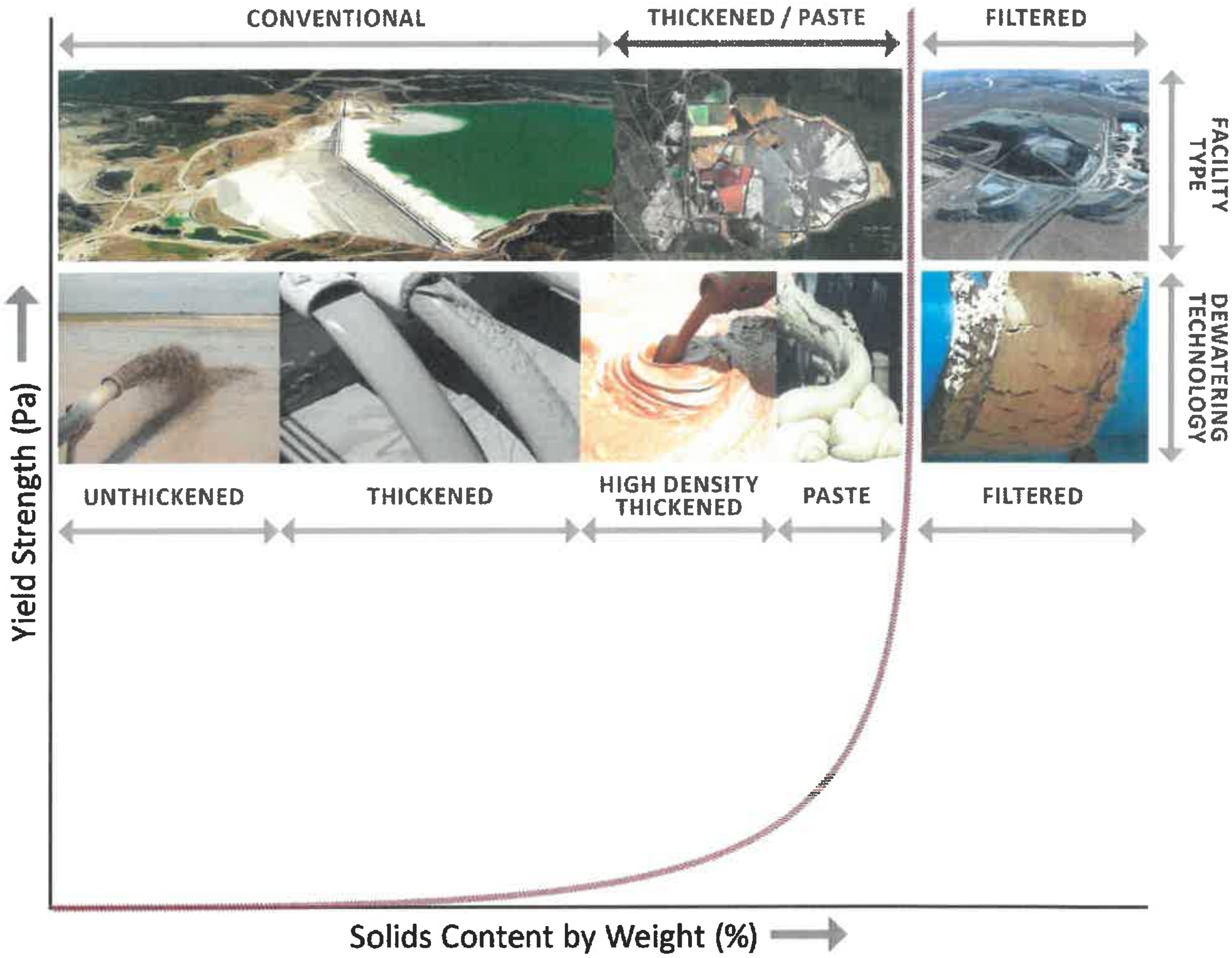
Approximately 90% of Canadian mines are managing their tailings as slurry contained by dams in surface impoundments (designated conventional tailings facilities in this study). A slurry is a mixture of tailings solids and water; conventional tailings slurry is a by-product of ore processing, typically has a *solids content* ranging from 20% to 40% and is most often delivered to the tailings facility in a pipeline for hydraulic discharge into the facility.

There is significant literature on conventional tailings dams, dam geometry and types, and dam design geometry options (e.g. downstream, centreline, upstream) considerations and this document does not try to duplicate that literature (for example, Vick 1990).

Tailings management strategies other than constructed dams and surface tailings facilities/ impoundments include in-pit disposal and underground backfill. If in-pit disposal or underground backfill are viable, they can be effective strategies and should be considered with their strengths and limitations. However, the scope of this report does not focus on in-pit, underground or *co-disposal* in great depth.

The continuum of dewatering of tailings and typical corresponding facility types are presented in Figure 1.1 based on solids content and tailings shear yield stress or strength (yield stress or strength is the applied pressure that must be exceeded to make a fluid flow and is further discussed in Appendix I).

Figure 1.1 Dewatered Tailings Continuum and Corresponding Facility Types



Photograph references:
Facility type images (left to right): KCB 2017, Google 2016 & © Digital Globe 2016, and Levac 2016
Dewatering technologies images: Fourie 2015 and Jewell and Fourie 2015

While the industry has coined several terms to describe dewatered tailings, this study has categorized dewatered tailings by the typical type of facility they were stored in for comparison, which include:

1. Conventional tailings facilities: facilities that accept unthickened or thickened slurry tailings, and are contained by engineered dams.
2. High-density thickened/paste tailings facilities: facilities that accept high-density thickened or paste tailings produced by a high-density thickener or a paste plant; the tailings are viscous materials with *yield strength* often in the range of 40 Pa to over 200 Pa. Tailings are generally contained by engineered dams, however, dams may be smaller if the facility takes advantage of the steeper *beach slopes*, if achieved.

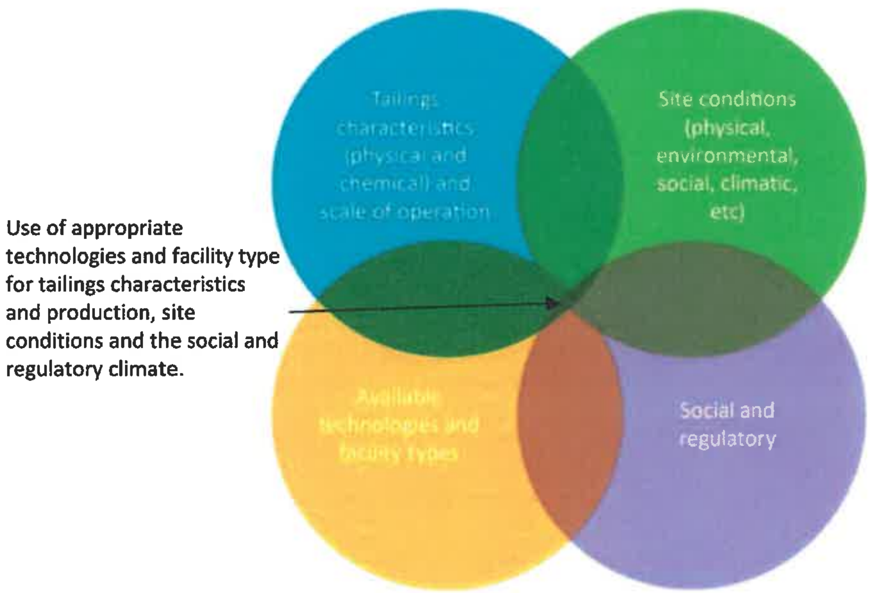
3. Filtered tailings facilities: facilities that accept and store tailings dewatered such that they behave like a soil, often produced close to *optimum moisture content* to facilitate compaction. Tailings are generally placed in self-supporting piles and have compacted *structural zones*.

These classifications are selected since they have a major influence on the types of containment suitable for tailings within the facility and the way in which water is managed in the facility. These are further described in Section 3.

2 CONSIDERATIONS FOR TAILINGS MANAGEMENT STRATEGY

Canada is geographically and climatically diverse, and tailings are not all created equal. The optimum tailings technologies and facility type for a given project should be chosen to reduce the overall risk profile of the project, particularly with consideration to long-term closure, and will be specific to the tailings and site characteristics. In addition, available technologies and the social/regulatory systems should be considered. This relationship is illustrated in Figure 2.1.

Figure 2.1 Tailings Management Strategy Considerations



A high-level review of some of these concepts is provided in the following sections and further technical details are appended. Note, this report focuses on the technical aspects of tailings management and does not address the social and regulatory system considerations.

2.1 Characterization of Tailings

An understanding of the physical and geochemical properties of tailings is required when selecting appropriate dewatering technologies. Physical properties include particle size distribution, clay type and content, *specific gravity*, rheology, plasticity, consolidation properties, and *hydraulic conductivity*. Geochemical properties include elemental and mineral constituents, acid generating potential, neutralization potential, and metal leaching potential. The reagents added during processing (e.g. *flocculants*, cyanide, etc.) also need to be considered and may influence the physical and geochemical stability of the tailings and composition of the pore water (water contained within the void space of the tailings).

Tailings produced by mines across Canada have a wide range of physical and geochemical properties. Typical tailings characteristics by commodity groupings are summarized in Table 2.1. Key physical and geochemical properties of the types of tailings are described further below. The listing is not meant to be exhaustive, but rather provides an overview of typical conditions.

Table 2.1 Typical Tailings Geochemical Classification by Commodity

Commodity	Physical Classification[1]	Geochemical Classification[1,2]			Typical Parameters of Interest[3,4]	Chemistry of Tailings Pore Water
		Sulphidic ML/ARD	Sulphidic ML	Non-Sulphidic Leaching		
Precious Metals						
Gold	Hard rock to altered rock	YES	YES	YES	Arsenic, Ammonia, Copper, Cyanide, Molybdenum, Sulphate	Fe, SO_4, As, Cd, Co, Cu, Ni, Mo, NH_3^+, CN, Se, Pb, Zn
Gold-Copper	Hard rock to fine	YES	YES	YES	Arsenic, Ammonia, Copper, Cyanide, Molybdenum, Sulphate	Fe, SO_4, Al, As, Cd, Co, Cu, Ni, Mo, NH_3^+, CN, Se, Pb, Zn
Base Metals						
Copper	Hard rock to altered rock	YES	YES	YES	Copper, Cobalt, Cadmium, Nickel, Zinc, Iron, Aluminum, Lead, Acidity	Acidity, Cu, Co, Cr, Fe, Mn, As, Mo, Zn, SO_4, Al, Cd, Pb
Nickel	Hard rock to altered rock	YES	YES	YES	Copper, Cobalt, Cadmium, Nickel, Zinc, Iron, Aluminum, Lead, Acidity	Acidity, Cu, Co, Cr, Fe, Mn, As, Mo, Zn, SO_4, Al, Cd, Pb
Zinc	Hard rock to altered rock	YES	YES	YES	Copper, Cobalt, Cadmium, Nickel, Zinc, Iron, Aluminum, Lead, Acidity	Acidity, Cu, Co, Cr, Fe, Mn, As, Mo, Zn, SO_4, Al, Cd, Pb
Molybdenum	Hard rock to altered rock	YES	YES	YES	Molybdenum, Fluoride, Aluminum	Mo, Al, F^-, SO_4, Fe, Cd
Polymetallic (Silver, Zinc, Lead, etc.)	Hard rock to altered rock	YES	YES	YES	Aluminum, Iron, Zinc, Lead, Cadmium, etc.	Al, Cu, Fe, Mn, Ni, Pb, Zn, SO_4, As, Cd, Cr
Industrial						
Coal	Coarse and fine	YES	YES	YES	Selenium, TSS	Al, Fe, Se, SO_4, NH_3, NO_3, As, Ni, Zn
Oil Sands	Coarse to ultra-fine	YES	YES	YES	TSS, Salts, Naphthenic acids, BOD, COD	PAH's, VOC's, Glycols, Nutrients
Potash	Coarse	NO	NO	YES	Brine salts, TSS	P, Mg, K, Na, Cl^-
Diamond	Hard rock to ultra-fine	YES	YES	YES	TDS, Barium, Aluminum, Iron, Manganese, Magnesium, Potassium, Phosphorous, Zinc, Sulphate	Al, Ba, Fe, Mg, Mn, K, P, Zn, Ni, Co, Cu, SO_4
Rare Earth	Hard rock	YES	YES	YES	REEs, TSS, Copper, Cadmium, Chromium, Lead	SO_4, Ra_{226}, NH_3, Th, F, La, Ce, Pr, Nd, Sm, Eu, Y, Cu, Cr, Pb, Cd, Fe
Uranium	Hard rock	YES	YES	YES	Radionuclides, Selenium, Sulphate, Arsenic, Nickel, Copper	Cu, Fe, SO_4, Mn, Se, As, Ra_{226}, U, Co, Ni, Pb, Pb_{210}, Zn
Iron Ore	Coarse and fine	YES	YES	YES	TSS, Copper, Iron, Manganese, Lead, Zinc	Fe, Cu, Mn, Pb, Zn, Acidity, SO_4
Aluminum Oxide (Red Mud Tailings/Bauxite Residue)	Fine	NO	YES	YES	TSS, Nickel, Arsenic, Chromium	Al, As, Ni, Cr, Alkalinity, Acidity, SO_4, Mn

Notes:
1. Discussed in Sections 2.1.1 and 2.1.2.
2. YES/NO refers to the potential for this type of tailings to exhibit the geochemical behavior.
3. Typical parameters of interest selected with the different commodity tailings is not an exhaustive list.
4. Toxicity is a key regulatory concern, along with parameter concentrations, however, toxicity is site-specific and is not defined in this report.

2.1.1 Physical Classification

The physical properties of the tailings influence the ease and technical feasibility of tailings dewatering technologies. Physical properties vary depending on several factors, including the properties of the ore (or commodity) being processed and the processing operation. Tailings can be generally characterized using index physical properties (i.e. *gradation*, specific gravity, and *Atterberg Limits* (plasticity)) and classified into the five major tailings types summarized in Table 2.2.

Table 2.2 Physical Classification of Tailings (ICOLD 2017)

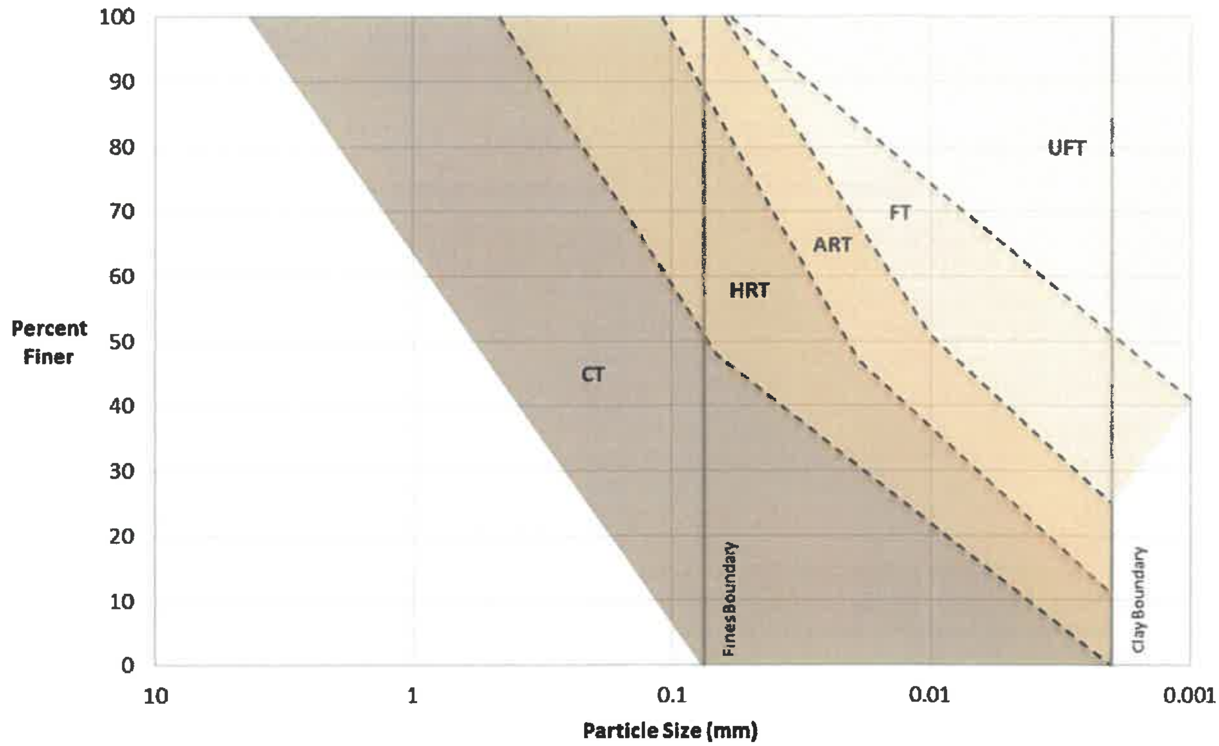
Tailings Type	Symbol	Description	Examples[2]
Coarse tailings	CT	Silty SAND, non-plastic	Salt, mineral sands, coarse coal rejects, iron ore sands,
Hard rock tailings	HRT	Sandy SILT, non-plastic to low plasticity	Copper, massive sulphide, nickel, gold,
Altered rock tailings	ART	Sandy SILT, trace to some clay-sized particles, low plasticity	Porphyry copper with hydrothermal alteration, oxidized rock
Fine tailings	FT	SILT, with trace to some clay-sized particles, low to moderate plasticity	Fine coal rejects, bauxite residue (red mud)
Ultra fine tailings	UFT	Silty CLAY, high plasticity, very low density and hydraulic conductivity	Oil sand (mature fine tailings - MFT)[1], phosphate fines, some kimberlite and coal fines

Notes:

1. Oil sands tailings are a product of using hot or warm water to extract bitumen from sand. The slurry waste is then hydraulically transported and stored within surface tailings ponds. The tailings fine fraction (MFT – *mature fine tailings*) accumulates closer to the centre of the pond. After several years, MFT, consisting of 86% water, may only settle to about 30% to 35% solids content.
2. Examples listed are not exhaustive. Some ore types will produce multiple streams of tailings that fit into multiple categories, for example, porphyry copper deposits can have a *coarse tailings* stream and/or an *altered rock tailings* stream.

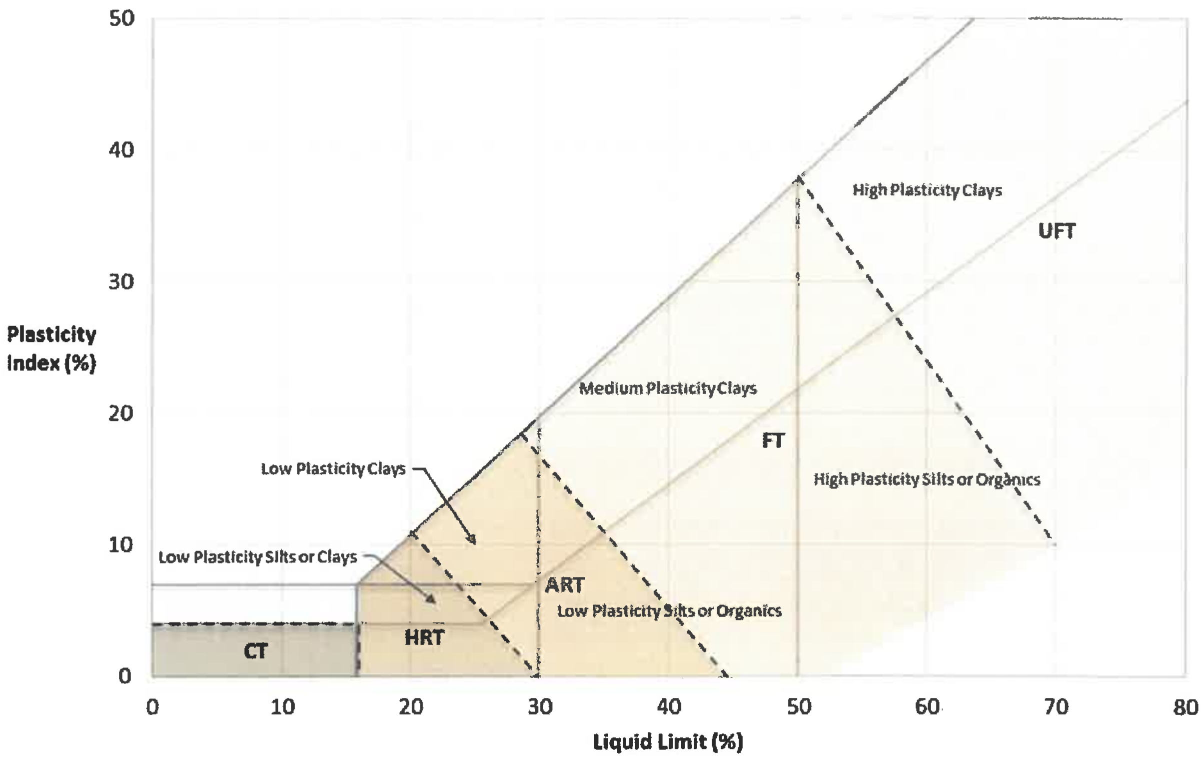
Particle size distribution (PSD) is the relative proportions of differently sized soil particles in a soil mass. The tailings PSD is influenced by (a) ore mineralogy, (b) alteration type, (c) degree of grinding in the milling process, and (d) clay fractions present in the orebody (or commodity host-body). Figure 2.2 presents the typical range of gradation for the various tailings types defined in Table 2.2.

Figure 2.2 Typical Tailings Classification based on Particle Size Distribution (ICOLD 2017)



Another physical property that influences the selection of dewatering technologies is the plasticity of the tailings (the behaviour of being easily shaped or moulded), as quantified by the Atterberg Limits. The plasticity is controlled by the proportion and types of clays present in the tailings. High plasticity tailings are characterized by poor settling, consolidation and dewatering characteristics, low hydraulic conductivity (they behave like a clay) and relatively high yield strengths at given *moisture content*. Figure 2.3 presents an Atterberg Limit chart indicating typical ranges for various tailings types that are listed in Table 2.2.

Figure 2.3 Tailings Classification based on Atterberg Limits (ICOLD 2017)



2.1.2 Geochemical Classification

The geochemical properties of the tailings and tailings pore water influence the water management and water treatment requirements for a tailings facility. Geochemical properties of tailings and pore water are influenced by:

- composition of the ore, which depend on the geology and type of the ore deposit and location and timing of mining;
- process methodology and conditions including particle size reduction, extraction of commodities and processing reagents and chemicals;
- additional post-plant processing, treatment and physical and chemical amendment;
- method of tailings deposition including particle size and mineral *segregation*;
- physical and geochemical composition of the initially deposited tailings and accompanying drainage, which depend on all of the above, especially minerals removed and liberated during processing; and
- physical and geochemical changes to tailings and accompanying drainage over time, which depend on initial composition, subsequent mitigation and physical and biogeochemical conditions in the storage facility.

Industry practice in tailings geochemical characterization methods are well documented in the Prediction Manual for Drainage Chemistry from Sulphidic Geologic Materials (Price 2009) and the Global Acid Rock Drainage (GARD) Guide (INAP 2009). The key considerations for the geochemical classification of the tailings in the context of this study are:

- types and concentration of sulphide and other primary and secondary minerals potentially resulting in poor water quality (above regulatory limits);
- types and relative concentration of acid generating and neutralizing minerals that determine the potential for acidic drainage and increased metal solubility;
- processing reagents (e.g. cyanide) and amendments (e.g. limestone); and
- potential changes to tailings physical and biogeochemical properties from solids-water-atmospheric-biologic interactions (e.g. the development of hardpan layers, mineral dissolution, etc.).

A generalized classification of tailings based on geochemistry is provided in Table 2.3.

Table 2.3 Geochemical Classification of Tailings

Tailings Type[1]		Description	Examples[2]
Sulphidic ML/ARD	Acidic (AG, ARD)	Tailings are already acidic and produce acidic drainage and elevated metal leaching.	Copper Cliff Central Tailings (base metal), Kidd Creek Mine (copper-zinc)
	Potentially Acidic (PAG, ARD)	Tailings contain sulphides, are potentially acidic, and are predicted to generate acidic drainage and metal leaching if exposed to aerobic weathering conditions. This classification also applies to cases where the onset of ML/ARD is uncertain.	Kemess South Mine (gold-copper); Canadian Malartic Mine (gold), Suncor (oil sands), Green's Creek Mine (polymetallic)
Sulphidic ML	Near-Neutral or Basic pH with Elevated ML (NPAG, NMD, SD)	Tailings contain sulphides but are predicted to produce near-neutral or basic pH drainage (there is sufficient neutralization present). Metal(loid) or non-metal leaching is expected at levels elevated above regulatory limits from oxidation reactions.	Snap Lake Mine (diamonds)
Non-Sulphidic Leaching		Tailings contain little to no sulphide and are predicted to produce near-neutral or basic pH drainage. Metal(loid) or non-metal leaching is expected from mineral dissolution or decay reactions at levels elevated above regulatory limits	Colonsay Mine (potash)
Low Reactivity (NPAG)		Tailings do not produce or are not predicted to produce acidic drainage or metal leaching at levels elevated above regulatory limits.	

Notes:

1. Tailings types have been simplified to classify tailings based on management strategies and potential water quality outcomes. The geochemical classifications of Acid Generating (AG), Potentially Acid Generating (PAG), Not Potentially Acid Generating (NPAG), ARD, *Neutral Mine Drainage* (NMD), and Saline Drainage (SD) fit within these categories.
2. Examples listed are indicative and not exhaustive.

Controls on sulphidic ML and sulphidic ARD are achieved by retarding the sulphide oxidation process by limiting the availability of either or both oxygen or water. Saturation of the tailings (often assumed to greater than 85%) is a standard and important control on limiting the generation of ML/ARD in these types of tailings, because it slows the diffusion of oxygen, resulting in less oxygen available for geochemical processes (INAP 2009).

2.2 Scale of Mining Operation

Paste and filtered tailings disposal strategies have been used at small-scale operations and small tailings facilities for over 30 years. In theory, these technologies and disposal strategies could scale-up to larger mining operations. In reality, there can be added complications and additional considerations to understand before up-scaling these technologies and disposal strategies. Some of these considerations are:

- operational complexity of large dewatering plants;
- variability in tailings properties;
- ability to achieve required moisture contents;
- transporting larger amounts of dewatered tailings longer distances;
- effective placement and compaction, if required, of high tonnage rates;
- water management of large tailings facilities (especially in wet climates); and
- unprecedented heights of alternative types of facilities.

2.3 Site Conditions

The site location and geographical characteristics are important factors when selecting tailings technologies and disposal strategies. Key site characterization considerations in tailings management approaches include:

- climatic conditions and resulting water management/balance;
- seismicity;
- geohazards;
- foundation conditions (geotechnical and hydrogeological);
- topography;
- potential downstream consequences (humans and environment); and
- presence of existing mine features (i.e. open pits).

Water management is arguably the most important aspect of tailings management, both from the viewpoint of physical stability as well as geochemical stability. Diligent management of water is required throughout construction, operations and post-closure. Poor water management is a root cause or contributing factor to many tailings dam safety incidents (USCOLD 1994), see also Section 3, Section 5 and Section 6.

Water management is dependent on site climate conditions. The management of flood flows, freezing conditions, and water surplus or deficit (see *water balance*) can often influence the selection of a tailings management strategy and use of dewatered tailings technologies. Water recovery, management, and treatment considerations can influence the overall risk profile and cost of tailings managment.

The tailings facility water management is inherently linked to the management strategy of the mine's other wastes (e.g. waste rock) and the broader mine water management strategy. Therefore, tailings facility water management needs to be considered in context of the overall mine.

Canadian topography ranges from mountainous terrain to prairie flatland; foundation soil and bedrock conditions range from competent bedrock to *glaciolacustrine* and varved sensitive clay soils. Site *seismic* conditions also have a wide range of variability across the country. The selection of technology tailings management strategy may be heavily influenced by the ability to construct dams, the foundation conditions, and the nature of site topography.

The selection and availability of an appropriate tailings facility site will also be influenced by the potential downstream risks from the facility. Proximity to permanent residences/populations and sensitive environmental receptors should be considered in conjunction with topographical features to help locate a tailings facility.

2.4 Tailings Technologies and Practices

This section provides a brief overview of the following:

- tailings dewatering technologies;
- tailings classification and segregation, including sulphide flotation processes;
- tailings and waste rock co-disposal approaches; and
- other tailings management strategies (including in-pit disposal, underground backfill, lake disposal, ocean disposal[1], etc.).

A brief overview of these technologies and practices is described in the following sections and additional details are included in Appendix I, however, this study focuses on the dewatering technologies.

2.4.1 Tailings Dewatering Technologies

Tailings dewatering technologies are summarized in Table 2.4. The dewatering process is a continuum where the behavior of tailings changes from fluid (slurry) to paste, and finally to soil as the percentage of water is reduced. The geotechnical properties of the tailings are an important consideration in the selection of applicable dewatering technologies. Appendix I provides further information regarding types of tailings and typical rheology parameters that are used in the selection of thickening and filtering equipment.

[1] This method is controversial, and is often opposed by affected communities and banned in certain jurisdictions. Non-governmental organization members of MEND's steering committee oppose this method.

Table 2.4 Summary of Tailings Dewatering Process Technologies

Dewatered State	Yield Strength (Pa)	Process Equipment	Transport Method
Unthickened	0	None - product of the processing plant with no additional dewatering effort	Pipelines, typically using centrifugal pumps
Thickened	0 - 40	Conventional thickeners and flocculants	Pipelines, typically using centrifugal pumps
High-Density Thickened	40 – 200	High-density thickeners and flocculants	Pipelines, typically using centrifugal or positive-displacement pumps
Paste	>200	Deep cone thickener or a combination of thickening and filtering	Pipelines, typically using positive-displacement pumps
Filtered	N/A	Vacuum or pressure filters	Trucks or conveyors

2.4.2 Tailings Classification and Segregation

Cycloning

Cycloning of tailings is the most commonly used method of classification to produce coarse sand that is used as competent fill for dam construction or other applications. Using cycloned sand for dam construction reduces the reliance on external *borrow* sources (and their resulting land disturbance) and reduces the quantity of tailings to be stored in the facility. Cycloning is commonly used for large-scale porphyry copper applications which have a relatively coarser-grind tailings sand and whose large operation size requires storage of large volumes of tailings and consequently requires large volumes of dam construction material.

(Sulphide) Segregation

Minerals high in *sulphides* can be separated from their lower-sulphide counterparts to produce separate tailings streams. This process can reduce the amount of potentially ML/ARD material that is handled, thus lowering the risk of sulphide oxidation, or ML/ARD, from the tailings. Tailings are separated, or segregated, usually through a flotation process, and the separate tailings streams can be managed independently. This may involve, for example, deposition and storage of the high sulphide tailings in saturated conditions, below the pond or water surface, and/or encapsulation of the high sulphide stream within the low sulphide tailings.

2.4.3 Tailings and Waste Rock Co-Disposal

Tailings and waste rock may be managed within the same facility typically with some degree of mixing to achieve the specific objectives for the facility. Generally, co-disposal involves one of the following:

- Encapsulating tailings within a waste rock dump through:
  - entrainment of the tailings into the voids of the waste rock;
  - inter-layering the waste rock with tailings; or
  - incorporation of discrete cells of tailings within the interior of the rock dump.
- Encapsulating waste rock within tailings in a tailings facility, generally to manage sulphidic ML and sulphidic ARD.

2.4.4 Other Tailings Management Strategies

Surface tailings management strategies include conventional tailings facilities, thickened/paste tailings facilities and filtered tailings facilities.

Other tailings management strategies (not reviewed in detail as part of this study) are those which do not require the construction of retaining dams or structural zones (in the case of filtered tailings) for containment. There are social, economic, environmental, and site limitations to these strategies which were not explored as part of this study.

In-Pit Disposal

In-pit tailings disposal can be used as the tailings management strategy in areas where (a) there is a pit present, (b) filling the pit with tailings does not pose operational health and safety risks (connected to active workings), or (c) filling the pit does not risk sterilization of the mine resources. Many new mine developments do not have existing pits to consider for the deposition and storage of tailings. Several examples of in-pit tailings disposal were collected as part of the Canadian facility review (ARCADIS 2015), however this cannot be widely applied in Canada due to availability and appropriateness of open pits.

Underground Backfill

Underground backfill using paste or filtered tailings may be a suitable tailings management strategy for underground mines that use compatible mining methods. As it relies on backfilling inactive (mined out) parts of the underground workings, tailings from initial underground mining must still be stored in a facility at the surface, although using tailings for underground backfill may significantly reduce the final size of this facility.

Lake Disposal

Lake disposal as a tailings management strategy can be effective to limit ARD under a narrow set of circumstances. It is typically only practiced in Canada at a handful of small mines which use small, non-fish bearing lakes of low ecological importance that have limited catchments, inflows and outflows.

Riverine and Ocean Disposal

Although historically used in Canada up to the mid 1990s, riverine and ocean disposal of tailings are now typically considered socially and environmentally unacceptable in Canada and we are not aware of any mines in Canada using these practices.

3 TAILINGS MANAGEMENT STRATEGIES

This section outlines the components of three main surface tailings management strategies:

1. Conventional tailings facility for storage of unthickened or thickened slurry tailings.
2. Thickened/paste tailings facility for storage of high-density thickened and/or paste tailings.
3. Filtered tailings facility for storage of filtered tailings.

3.1 Conventional Tailings Facilities

Overview

Conventional tailings facilities involve delivery, often in a pipeline, of unthickened or thickened slurry (typically ~20% to ~50% solids content by weight, and up to 60%) from the *ore processing facility*[1] or thickener to the tailings facility. The tailings are deposited hydraulically, in a loose state, behind containment dams. Tailings are deposited either above or below water and will typically segregate with coarser material settling near the discharge point and finer material being transported further from the discharge point. This segregation can be an advantageous or detrimental aspect of conventional deposition. Water liberated from the slurry collects in a pond on the tailings surface and (a) evaporates, (b) is discharged from the facility, or (c) is reclaimed to the ore processing facility via a reclaim pond. Figure 3.1 shows a typical schematic of a conventional tailings facility.

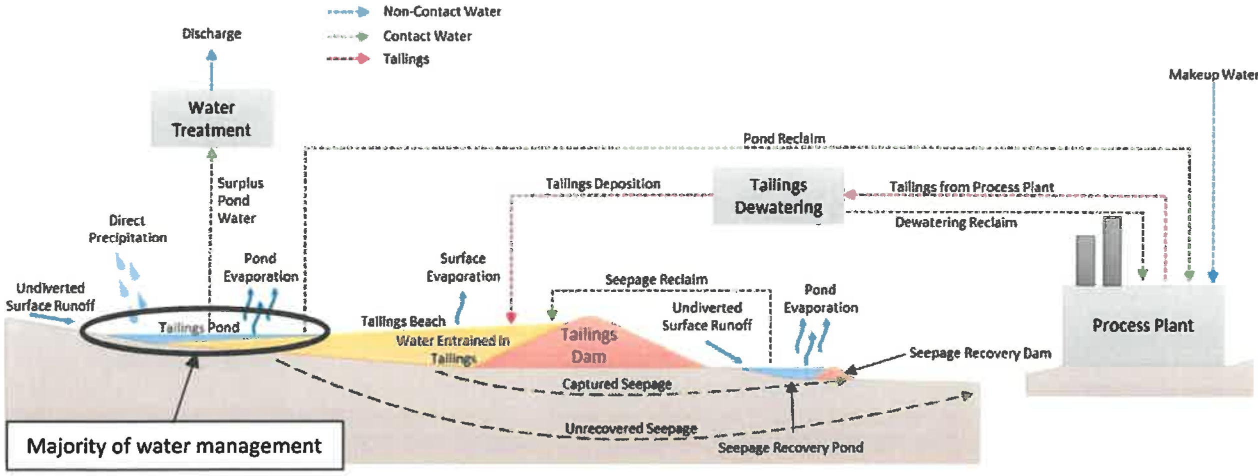
Approximately 90% of Canadian mines are managing their tailings as slurry deposited in conventional tailings facilities.

Dams may be constructed from locally excavated material, mine waste rock, the tailings themselves, or a combination of materials.

This study does not delve into comparing the different types of containment structures and material types for conventional facilities (e.g. upstream, downstream, centreline, cycloned sand, waste rock). Containment dam design is an important part of risk management associated with tailings facilities that should also be considered during selection of a tailings management strategy.

[1] Not all mines produce ore. However, ore processing facility is the term used in this study for the facility where tailings are produced.

Figure 3.1 Schematic for a Conventional Tailings Facility



Processing

Thickeners can be used to increase the solids content prior to transporting the slurry to the tailings facility. Thickening is usually driven by a need for water recovery as the deposited tailings typically have similar properties to unthickened slurry. The optimum solids content for a slurry can be based on a trade-off between water recovery, pumping rate, pump type (centrifugal or positive displacement), thickening time, tailings beach slope, control of segregation of tailings, and cost. Thickeners are usually of a conventional type or a high rate type (shown in Figure 3.2). Both can manage large inflow rates and can achieve up to about 60%-65% solids content, but produce a slurry with no or very low yield strength. More information on thickening can be found in Appendix I.

Figure 3.2 High Rate Thickeners

Image reference: (Vietti Slurrytec 2015)

Containment

In a conventional facility, tailings are deposited in an initially saturated state behind dams. Depending on the local climate and hydrogeological conditions within the facility and its foundation, the tailings may remain saturated or may desiccate or *drain-down* and become partially-saturated.

Depending on the tailings particle size distribution, deposited tailings slurry will segregate, with coarse/heavy particles settling close to the discharge location and fine particles settling further away (potentially in a reclaim pond). This segregation can be used to create a well-drained zone close to the dam, thus enhancing the dam stability. Segregation can also create problems, such as dusting of dry, sandy beaches, concentration of sulphides, and poor consolidation and low strength of the slimes areas.

However, coarse tailings, often from the beach near the dam, can be used as compacted fill to construct the dams.

Water Management / Geochemical Control

A best practice goal from a dam safety perspective is to store as little water as possible with the tailings. This strategy could be combined with an external water management facility.

However, conventional tailings facilities usually contain reclaim water in addition to tailings solids. The reclaim pond collects (a) water that is liberated from the tailings slurry, (b) precipitation that falls on the facility, (c) runoff from the undiverted catchment of the tailings facility, and (d) other inflows from the mining operation. The pond size is dependent on tailings throughput and slurry *water content*, topography, seasonal climate variations, ability to discharge water, geochemical control strategy, site-wide water balance, and the water supply requirements of the ore processing facility.

Often, the stability of tailings dams is reliant on maintaining wide tailings beaches between the pond and the dams (the tailings beach is shown in Figure 3.1), which therefore, requires control of the reclaim pond and site-wide water balance.

The water balance, particularly in Canadian environments, is strongly influenced by the spring runoff and fall and winter storms. In northern conditions, snow, freezing of tailings and ice formation/melting also impact the water balance. By design, conventional tailings facilities store and attenuate these flows to provide consistent water reclaim to the ore processing facility during drier periods and flood storage prior to water treatment and release. Management of catchment runoff and other site *contact water* reporting to the tailings facility is also required. In wet climates, release of surplus water (with or without treatment) is usually required to minimize the accumulation of water in the facility or on the mine site.

Most conventional tailings facilities have smaller dams downstream of the main impoundment to intercept and collect seepage water.

The geochemical characteristics of the tailings and the reagents used in processing will also impact the water management and water treatment strategy during operations. Some projects use pond water to maintain saturation of sulphidic tailings to minimize oxidation and reduce ML/ARD. Ponding is also a beneficial strategy to manage the residence time of water in the facility to take advantage of chemical degradation or attenuation mechanisms in the tailings pond water (such as cyanide degradation, or secondary mineral formation).

Closure

Closure of a tailings facility will depend on climate, site conditions, facility type, tailings properties and preferred end land-use. As such, considerations for closure will depend on many aspects, of which facility type is only one. Closure of conventional tailings facilities typically includes installing a *cover* and re-vegetating the surface of the tailings. Long-term monitoring of the facility is required to assess physical, geochemical and ecological stability.

Recently in the industry, there has been a push to close conventional facilities "dry," which describes closure without a water pond. This greatly reduces the consequences of a dam failure by reducing the runout potential of the tailings in the event of instability. Geochemical stability of dry closed tailings impoundments that store tailings with the potential to produce poor water quality can be managed using phreatic covers (inert soil or tailings covers that control oxygen diffusion by maintaining saturated pore space) and/or oxygen consuming covers. Long-term cover performance has been a challenge with dry closure, however the technology and approaches continue to improve (KRS 2016).

If ponded water has to be kept on the dam, then measures such as maintaining the closure pond as far away from the dam crest as possible, is good practice for physical stability.

In the absence of a water pond, the management of surface water runoff is often the most significant physical risk on closure.

3.2 High-Density Thickened/Paste Tailings Facilities

Overview

High-density thickened/paste tailings facilities involve delivery, in a pipeline, of a high-density thickened or paste tailings (typically ~60% to ~75% solids content by weight and *shear yield stresses* from 40 Pa to 200 Pa) to the tailings facility. Due to the high shear yield stress of the tailings, positive displacement pumps may be required. The tailings are deposited hydraulically, in a loose state, and beached at somewhat steeper slopes than unthickened slurry.

Containment dams are still required, but can be smaller than those with conventional tailings facilities if beach slopes can be taken advantage of. High-density thickened/paste tailings facilities are usually operated with no or minimal ponds on the tailings surface. Compared to conventional tailings facilities, less water is released from the deposited tailings as they consolidate. This water, along with precipitation and runoff, collects in ponds on the tailings surface next to the dam, or is directed off the surface to external collection ponds where it may be reclaimed to the ore processing facility or discharged. Similar to conventional facilities, the containment dam design for these facilities can vary and is not the focus of this study.

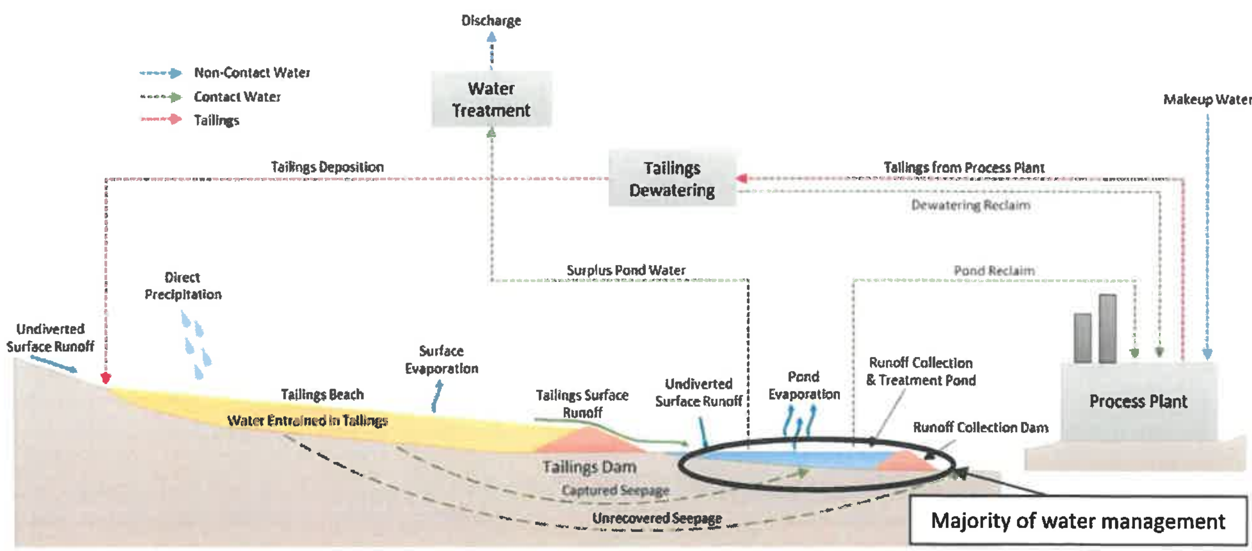
Paste tailings can be produced using high-density thickeners or a filter plant and typically aim to have ~70% to ~75% solids content. Multiple definitions of paste tailings have created considerable confusion in the tailings design community. Current definitions hold that paste tailings are achieved when a solids content is reached such that:

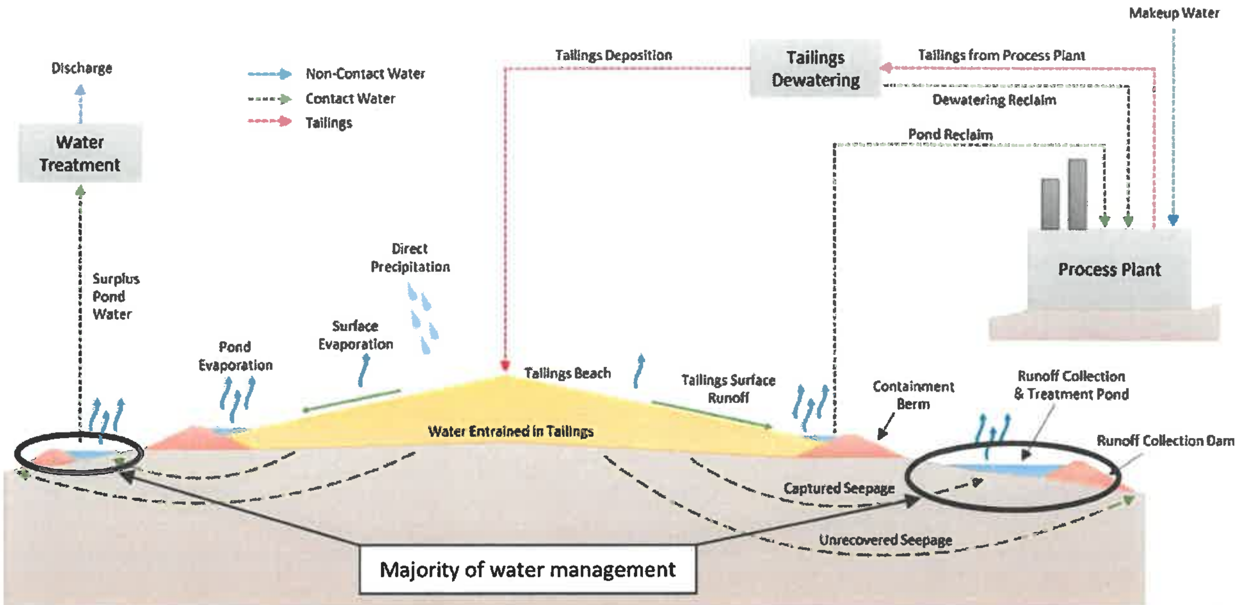
- the tailings will "bleed" limited volumes of excess water. This can be tested in laboratory "jar" settling tests;
- the yield stress is approximately 200 Pa and positive displacement pumps are required for transport (see Appendix I); or
- a *slump* of 150 mm is achieved in a concrete slump test.

Figure 3.3 illustrates two types of thickened/paste tailings facilities — one with a side-hill deposition, or tailings placement, and the second with a central cone deposition.

Historically, this is the least common facility type in Canada. Based on our research, consistency of tailings product over time and lack of ability to achieve steep tailings slopes are the main concerns with high-density thickened/paste tailings.

Figure 3.3 Schematic of Thickened/Paste Tailings Facility (top: side-hill deposition; bottom: central cone deposition)



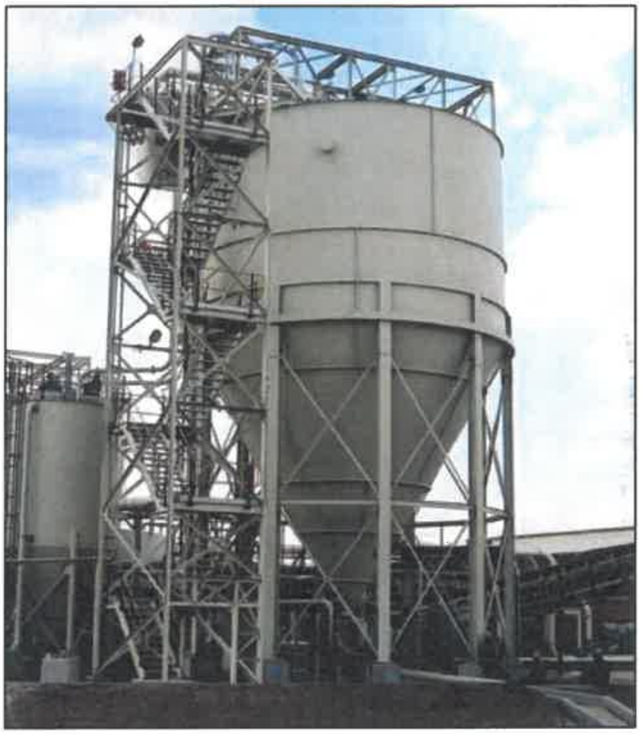


Processing

High-density thickeners, *high compression thickeners*, or deep cone thickeners are used to achieve the high solids contents for *high-density thickened* and paste tailings. An example of a deep cone thickener is shown in Figure 3.4. Thickeners alone often cannot achieve the required solids content for paste tailings and in some cases, a mixture of thickeners and filters are used to achieve the target solids content (between 60% and 70%, depending on the tailings properties). More information on thickening can be found in Appendix I, filter plant equipment is described in Section 3.3 and in Appendix I.

Producing a consistent filter product is a major challenge with the processing as small changes in the orebody geology, especially *clay-sized particle* content, can greatly influence the paste characteristics, such as yield strength and associated beaching angle.

Figure 3.4 Ultra High Rate Thickener (Deep Cone Paste Thickener) (EIMCO E-CM™ - Jewell and Fourie 2015)



Containment

Similar to a conventional facility, the tailings are placed in a loose, saturated state and, depending on climate and hydrogeological conditions, may remain saturated or desiccate/drain-down and become partially-saturated.

The deposited high-density and paste tailings will be somewhat denser than slurry placed tailings over the upper 5 m to 10 m of the deposit. However, due to self-weight consolidation paste and slurry tailings deposits often achieve a similar final density at depth and this reduces the often-cited advantage that paste facilities require significantly less storage than slurry tailings. In fact, high-density thickened/paste tailings facilities may require a larger footprint than a conventional tailings facility to accommodate a lower perimeter dam height.

The high-density thickened or paste tailings are deposited hydraulically, or loosely, and beach, or settle, at somewhat steeper slopes than conventional tailings slurry. In theory, the beach slope can be up to 4%, however, in practice steep slopes are only achieved for a short distance and the remaining beach is sloped at less than 2%. The steeper beach slope of a high-density thickened/paste facility, compared to a conventional slurry beach, provides an opportunity to store tailings above the dam elevation, which reduces the footprint and height of the dam.

Containment dams are constructed from material extracted from the local area, and/or mine waste rock, and usually not from the tailings themselves. Much less process water is managed in a paste containment facility and this can significantly reduce the consequence from a potential failure of the structure compared to a conventional tailings facility. It is often possible to collect the water near water retaining perimeter dams and/or discharge the water to separate water storage facilities.

High-density thickened and paste tailings should be, by definition, largely non-segregating (i.e. fine and coarse particles do not separate during deposition), however minor segregation could still occur depending on the tailings particle size distribution and solids content at deposition. Non-segregating behaviour can be an advantage in managing geochemical issues through higher moisture retention.

High-density thickened/paste tailings facility dams should be designed, operated and closed with the same considerations as a conventional tailings facility.

Water Management / Geochemical Control

Compared to conventional tailings facilities, less *bleed water* and *consolidation water* is released from the deposited tailings. This water, along with precipitation and runoff, collects in ponds on the tailings surface often near the perimeter dams, or can be directed off the surface to external collection ponds. The reclaim pond size on the tailings surface is dependent on topography, tailings surface geometry, hydraulic design of water conveyance structures, and seasonal climate variations.

In addition to the reclaim pond on the tailings facility, collection ponds downstream of the tailings facility are required to collect and manage runoff from the tailings facility. Collection pond sizing is dependent on topography, seasonal climate variations, ability to discharge water, water quality, the mine site-wide water balance and back-up water supply to the ore processing facility. These collection ponds can be large when the overall mine water balance is positive (even if only seasonally).

The non-segregated tailings should have an overall lower average hydraulic conductivity, which can provide for a higher water retention capacity and subsequent reduction in the oxygen diffusion and water infiltration, which is beneficial for sulphidic ML/ARD control. However, the tailings beach surfaces are exposed to oxygen, which promotes sulphide oxidation.

Closure

Closure of thickened/paste tailings facilities requires similar considerations as those of conventional tailings facilities. There is not currently a precedent for final closure of a high-density thickened/paste tailings facility in Canada.

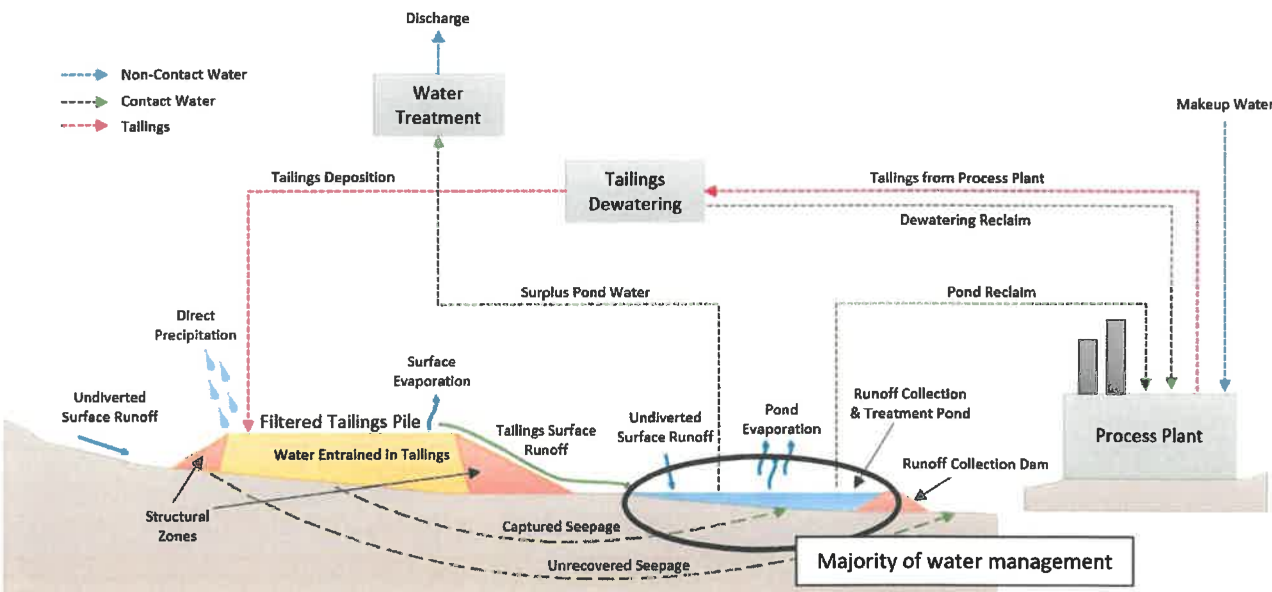
3.3 Filtered Tailings Facilities

Overview

Filtered tailing facilities involve delivery, by truck or conveyor, of tailings that are dewatered such that they are partially-saturated and act like a soil rather than a fluid. Filtered tailings are typically dewatered to more than 80% solids content, often near optimum moisture content, to facilitate compaction. Typically, the filtered tailings themselves form the containment structure ("structural zones"). Facility seepage and runoff are collected and managed in external collection ponds. Figure 3.5 shows a schematic of a typical filtered tailings facility.

Historically, this has not been a common tailings facility type in Canada. However, filtered facilities are being proposed and constructed more frequently in Canada.

Figure 3.5 Schematic of a Filtered Tailings Facility



Processing

Of all the discussed tailings dewatering technologies, filtering produces tailings with the lowest moisture content. The ability to filter tailings is influenced by the particle size and the plasticity; finer tailings and higher-plasticity tailings that contain greater amounts of clay-sized particles are more challenging to filter. As well, high-plasticity tailings (those that are more malleable) may become sticky after being filtered, potentially making them challenging to manage at the filter plant during transportation and placement, especially in wet environments. Technologies broadly include vacuum filters and pressure filters. Figure 3.6 shows an example of a vertical plate pressure filter used for tailings.

Vacuum filters include drum, disc or horizontal belt filters. Vacuum belt filters are less expensive to operate and are a continuous process, but typically cannot achieve the optimum water content for machine compaction of the tailings. Therefore, vacuum filtration is generally limited to coarser tailings (which are more easily dewatered and may drain more rapidly after placement) and dry climates (where air-drying of the placed tailings further reduces the moisture content after placement). The efficiency of vacuum filters decreases at higher altitudes although they have been used on tailings at sites 3,000 m above sea level.

Pressure filters can apply higher pressure to achieve moisture contents appropriate for compaction of tailings using conventional fill placement techniques of dump, spread, and compact. A typical filter cycle includes filling, pressure filtration (squeezing water out), potentially air blowing (decreasing saturation by blowing air through the material), discharging, and cleaning. They are more expensive and energy-intensive to operate, and run in a batch process rather than as a continuous process. Hence, pressure filters have been traditionally used for smaller production operations (<5,000 tpd). Recent projects, however, have seen trial application of larger production units (not in Canada).

Figure 3.6 Vertical Plate Pressure Filter

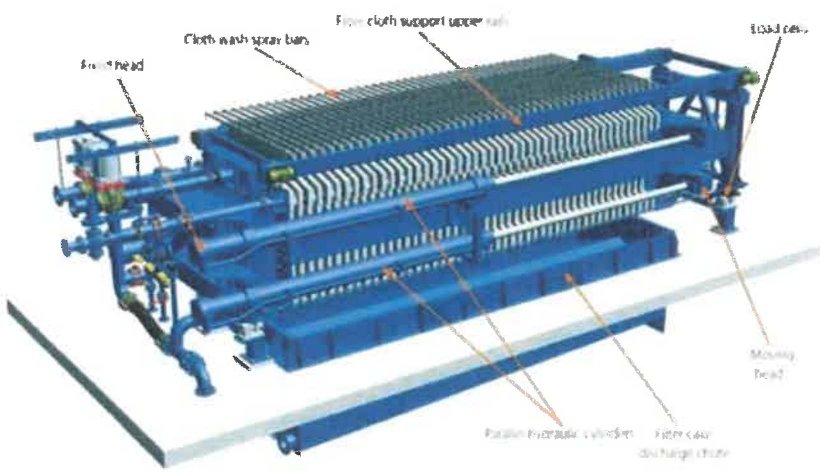


Figure 1: Vertical Plate Pressure Filter

Image reference: (CERIG 2013)

Containment

If filtered tailings are placed in a stand-alone facility (pile/stack), the outer slopes must maintain structural stability (similar to a dam or a waste dump), particularly under seismic loading conditions. To maintain structural stability, tailings must be well-drained and/or compacted for *static* stability and to prevent *liquefaction*. Drainage alone should not be relied upon to prevent liquefaction, especially in wet climates. Therefore, a portion of the tailings, needed for the external structural zone of the pile, needs to be dewatered to allow for compaction (i.e. close to, or slightly less than optimum moisture content). The remaining tailings can be placed in the interior and can be slightly wetter and lightly compacted. It is important to determine at the start of pile construction what the final geometry is so that the zone of compaction is well defined.

Water Management

During filtering, water is recovered and is re-used in the ore processing facility. Collection ponds downstream of the tailings facility are required to collect and manage runoff from the tailings and local catchment. The size of the collection ponds depends on topography, seasonal climate variations, ability to discharge water, water quality, the mine site-wide water balance and water supply to the ore processing facility. These collection ponds may be large when the overall mine water balance is positive (even if seasonally).

Conventional tailings facilities have reclaim water ponds within the tailings impoundment where *fine tailings* particles settle. During storm events, runoff from the beach collects in the reclaim water pond and tailings particles brought into suspension will settle in these ponds. Filtered tailings facilities do not have this feature. Runoff from a filtered tailings surface may be high in suspended tailings particles that will settle out in the external water collection pond, requiring further management. During review of the filtered tailings facility case histories, erosion control was noted as a challenge during rain events; and sediment control in collection ponds requires dredging and maintenance. However, progressive reclamation of filtered tailings facility slopes can be used to control erosion; it can also control dust and ML/ARD. This is not possible on filtered tailings surfaces that have active deposition using walking stacker conveyors.

Managing high-intensity storm events on large, filtered tailings facilities is difficult, because filtered tailings facilities, by design, typically do not have substantial flood storage capacity. The objective during high-intensity storms is to route runoff on the top surface of the pile and then control discharge to prevent uncontrolled flow over the outer embankment crests from eroding the steeper, structural zones (the outside) of the pile. This can be achieved by sloping the pile near the embankments towards the interior of the pile. In turn, the interior is sloped to direct runoff towards collection ditches and ultimately the collection ponds. During high-intensity storm events, however, the collection ditches may not realistically be able to pass peak flows. Therefore, the filtered tailings surface, if available, should be graded so that a significant volume of water can be attenuated on top of the pile without overtopping the structural zones. This storage would only be used to attenuate high intensity peak-inflows when the capacity of the collection ditch is exceeded.

In some cases, perhaps due to space restrictions or reserve increases, filtered tailings facilities have a final geometry which results in a pile where nearly all the surface is sloping, this can greatly complicate storm water runoff management and needs to be factored into the design at an early stage.

Geochemical and Other Controls

Filtered tailings are placed partially-saturated, and as such:

- typically require active dust management; and
- the tailings are exposed to oxygen, which can lead to ML/ARD depending on the tailings geochemical properties.

Dust can be managed during operation using conventional dust management practices including one or more of the following: compaction, dust suppressants (surfactants), vegetation, hay or straw placement, and progressive rehabilitation.

While tailings in the filtered facilities are less saturated and have a higher potential for ML/ARD, certain physical aspects of filtered tailings facilities offer benefits to offset this increased risk.

Sulphidic tailings will also consume oxygen and potentially limit the penetration depth of oxygen within the facility. When placed and compacted, filtered tailings can also have a low hydraulic conductivity which can reduce the volumetric flow of water through the tailings.

Closure

Filtered tailings offer control on construction sequence and final geometry of the tailings facility. Therefore, progressive reclamation of the surface is possible, which can reduce erosion caused by runoff, dust and ML/ARD. However, larger-scale operations using mobile stacking conveyors for transporting and placing filtered tailings, and facilities that are expanding outwards as well as upwards require a large active area for placement, and consequently are not suitable for progressive reclamation over a large part of the pile.

Physical stability of the filtered tailings facility is good if the tailings are well drained and adequately compacted. There is a lower risk associated with geotechnical instability than conventional facilities that have closure ponds, as there is not a permanent surface water pond and the tailings are less mobile.

Generally, there is little post closure settlement and covers can be placed soon after tailings placement stops.

4 CASE HISTORY REVIEW OF TAILINGS MANAGEMENT TECHNOLOGIES AND PRACTICES

4.1 Overview

The objective of the case history review is to examine and compare projects that use tailings dewatering technologies. Appendix II includes a summary table of the reviewed case histories (Canadian and international) and more detailed descriptions of selected case histories.

Primary items of interest for each project include:

- site conditions, including climate, deposit type, geological setting, geohazards, seismicity and sensitive environmental issues;
- tailings properties, including tailings dewatering methods, and physical (geotechnical) and geochemical characteristics;
- operational management and closure strategies, including tonnage, required infrastructure, material handling and placement procedures, closure plan, and economic information; and
- the reason for selecting the tailings dewatering technology and the level of success in achieving the design goals.

Case histories include operating, closed, and proposed projects. Information for this review was collected through:

- a questionnaire sent to approximately 260 recipients in mining companies requesting basic information on site characterization, tailings properties and tailings dewatering technologies. Thirty-six (36) replies were received;
- a comprehensive search of KCB's library and previous projects files (more than 60 years of projects);
- a comprehensive literature search conducted by KCB's professional librarian;
- contacts within the mining industry;
- contacts with KCB mining clients;
- contacts with associations and organizations such as International Commission on Large Dams (ICOLD), Mining Association of Canada (MAC), Canadian Dam Association (CDA); and
- contacts with provincial, territorial and federal government agencies.

Table 4.1 lists the mines that use tailings dewatering technologies in Canada. Appendix II includes a more comprehensive summary table of the Canadian and international dewatered tailings case histories.

Table 4.1 Canadian Mines that Use Dewatering Technologies for Surface Tailings Disposal

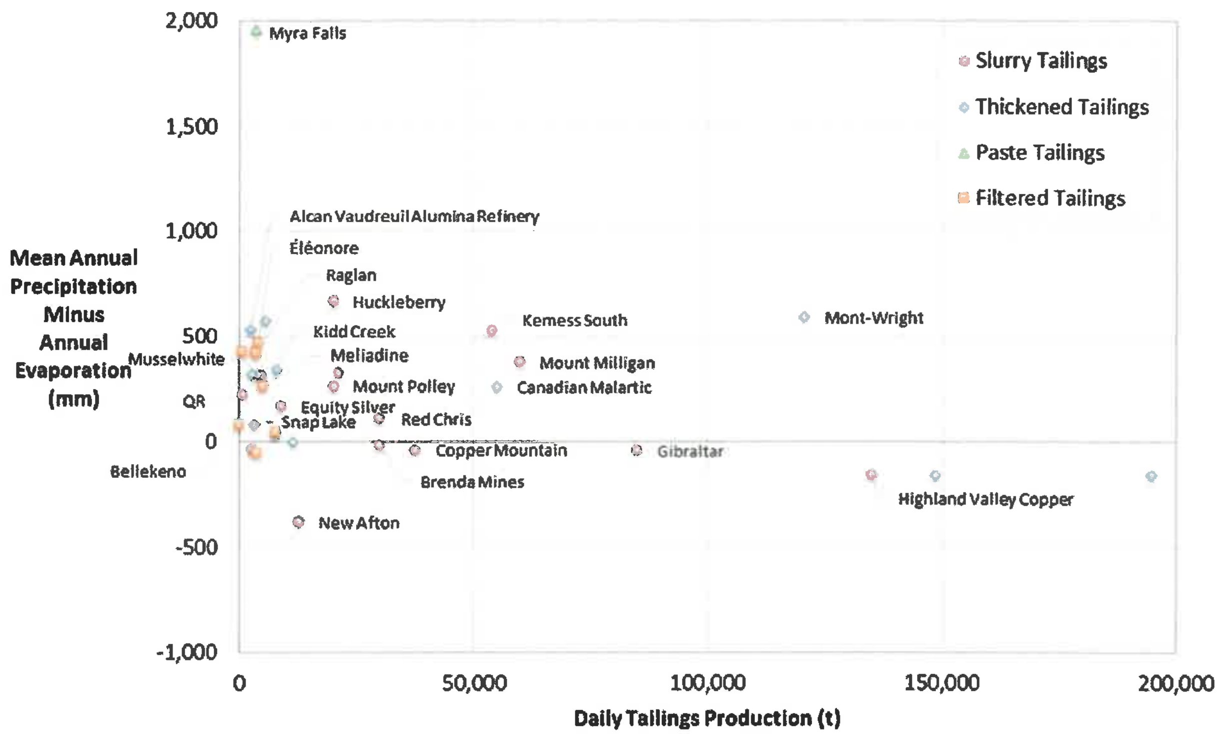
Dewatering Technology (see Figure 1.1)	Number of Canadian Facilities	Project	Owner	Commodities	Province	Mine Status	Tailings Production Rate (tonnes per day - tpd)	Facility Type (see Figure 1.1)	Questionnaire Received
Thickened (above 50% solids by weight)	7	Selbaie Mines	BHP	Au, Cu, Zn, Ag	QC	Closed	7,600	Conventional	No
		Meadowbank	Agnico Eagle Mines Limited	Au	NU	Operating	11,300		Yes
		Voisey's Bay	Vale Mines	Ni	NL	Operating	6,000		Yes
		Mont-Wright	ArcelorMittal Exploitation minière Canada s.e.n.c	Fe	QC	Operating	120,419		Yes
		Muskeg River	Canadian Natural Resources Limited	Oil Sands	AB	Operating	194,790		Yes
		Jackpine	Canadian Natural Resources Limited	Oil Sands	AB	Operating	148,500		Yes
		Sudbury Integrated Nickel Operations	Glencore Canada	Ni, Cu, Co, Pt	ON	Operating	6,027		Yes
High-density Thickened (above 60% solids by weight)	5	Musselwhite	Goldcorp Inc.	Au	ON	Operating	4,000		Yes
		Snap Lake	De Beers SA (Anglo American plc)	Diamonds	NT	Operating	3,150		No[1]
		Canadian Malartic	Yamana Gold Inc./Agnico Eagle Mines Ltd.	Au	QC	Operating	55,000		Yes
		Vaudreuil Alumina Refinery	Rio Tinto Aluminum	Al	QC	Operating	2,465	High-Density Thickened/ Paste	No
		Kidd Creek	Glencore Canada	Cu/Zn	ON	Operating	8,000		No
Paste[2] (above ~70% solids by weight, requires positive displacement pump)	1	Myra Falls[3]	Nyrstar	Zn/Pb/Cu	BC	Care and Maintenance	3,600		Yes
Filtered (above 80% solids by weight, cannot be pumped)	9	Minto	Capstone Mining Corp.	Cu/Au	YT	Operating	3,800	Filtered	No[1]
		Raglan	Glencore Canada	Ni/Cu	QC	Operating	4,000		No[1]
		Bellekeno	Alexco Resource Corporation	Ag, Au, Pb, Zn	YT	Care and Maintenance	321		No
		Fording River[4]	Teck Coal Limited	Coal	BC	Operating	–		Yes
		Line Creek[4]	Teck Coal Limited	Coal	BC	Operating	–		Yes
		Coal Mountain[4]	Teck Coal Limited	Coal	BC	Operating	–		Yes
		Eagle River	Wesdome Gold Mine Ltd./ Mines d'Or Wesdome Ltee	Au	ON	Operating	700		No[1]
		Éléonore	Goldcorp Inc.	Au	QC	Operating	4,000		Yes
		Meliadine	Agnico Eagle Mines Limited	Au	NU	Construction	5,000		Yes

Notes:
1. Information important to the study was provided by phone conversations with mine employees.
2. Does not include operations that produce paste for underground backfill.
3. Paste used to increase the storage capacity of a conventional tailings facility.
4. Filter coarse fraction of waste stream.

4.2 Climate and Production Rate Trends in Tailings Technologies

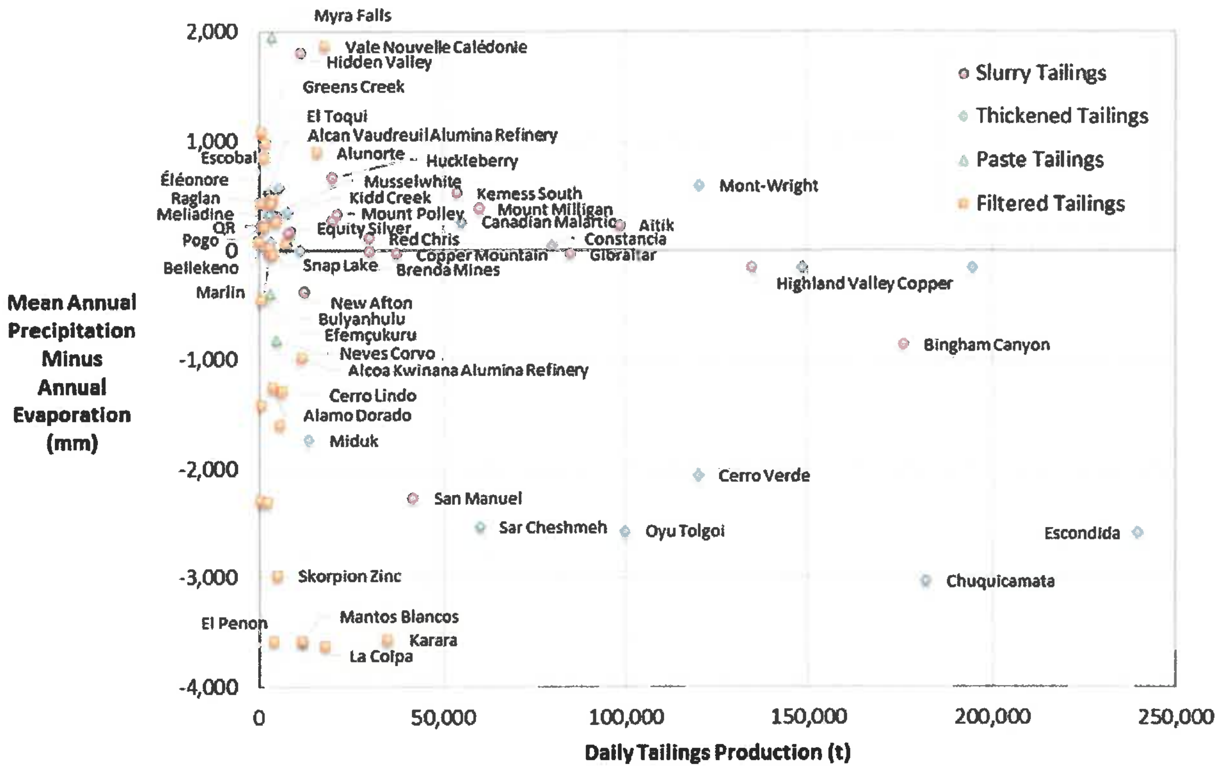
The Canadian projects which employ conventional and tailings dewatering technologies are presented in Figure 4.1; all project case studies are presented in Figure 4.2.

Figure 4.1 Canadian Project Summary



Note: only facilities that are included in the case history review or provided a questionnaire response are included in the graph.

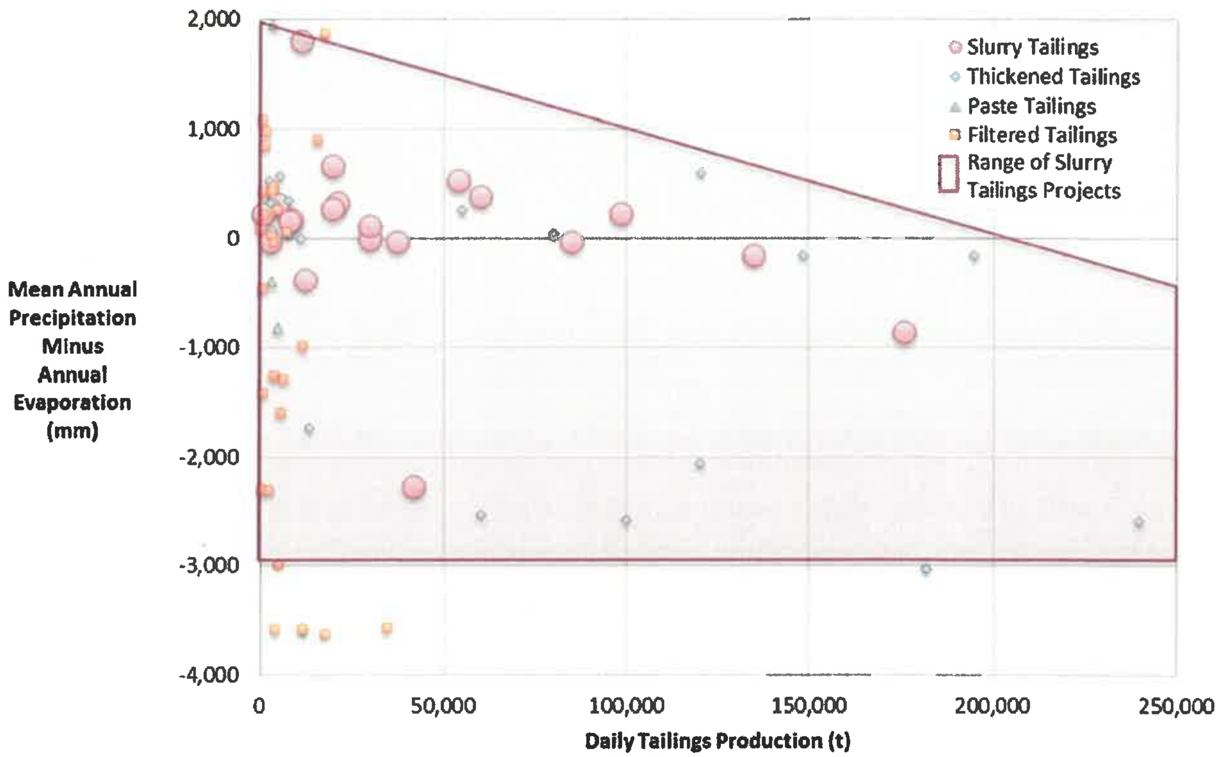
Figure 4.2 Projects Summary – Canadian and International



Note: only facilities that are included in the case history review or provided a questionnaire response are included in the graph.

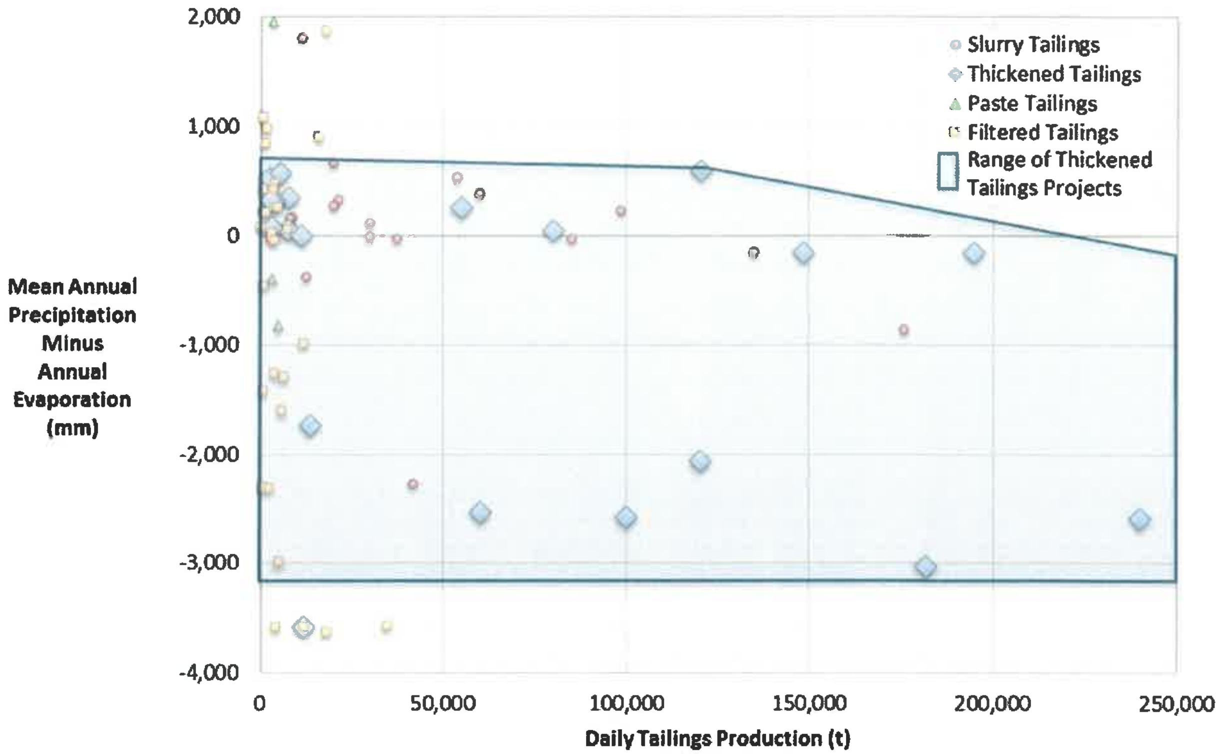
Key trends in the application of conventional and tailings dewatering technologies are illustrated in Figure 4.3 to Figure 4.6.

Figure 4.3 Range of Slurry Tailings Applications (Conventional Facilities)



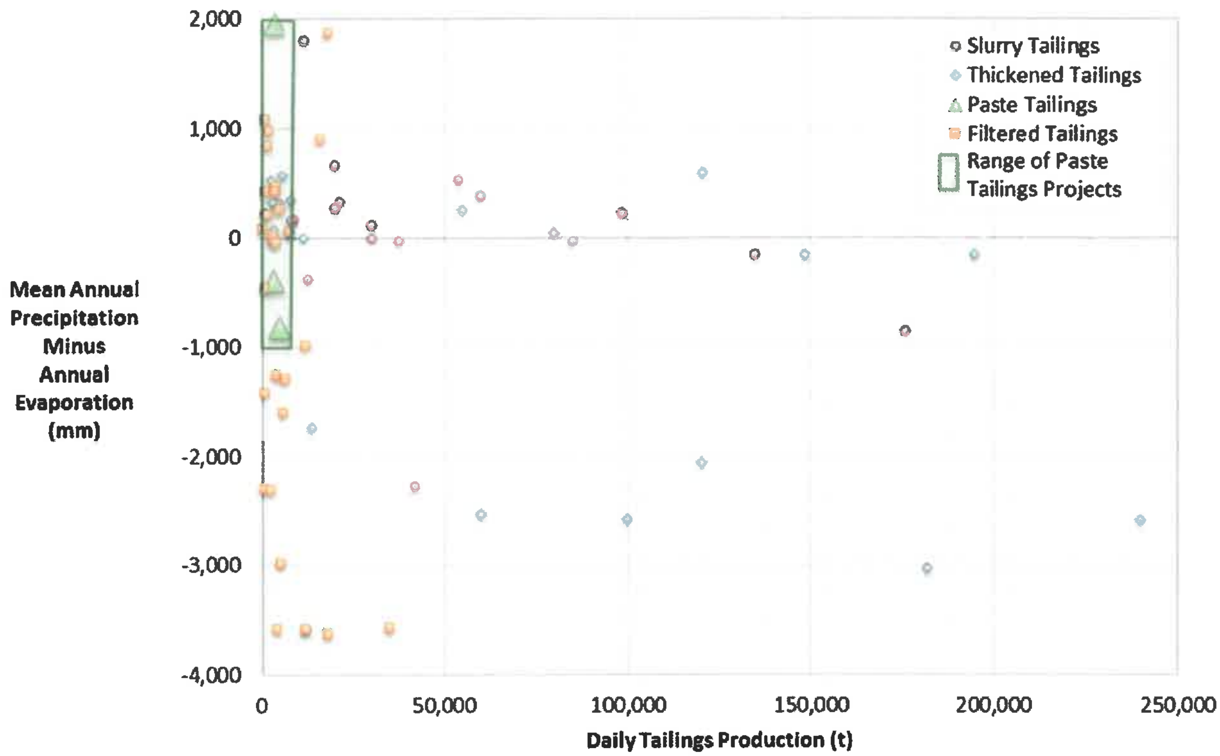
Note: only facilities that are included in the case history review or provided a questionnaire response are included in the graph.

Figure 4.4 All Projects – Range of Thickened Tailings Applications (Thickened Tailings in Conventional Facilities)



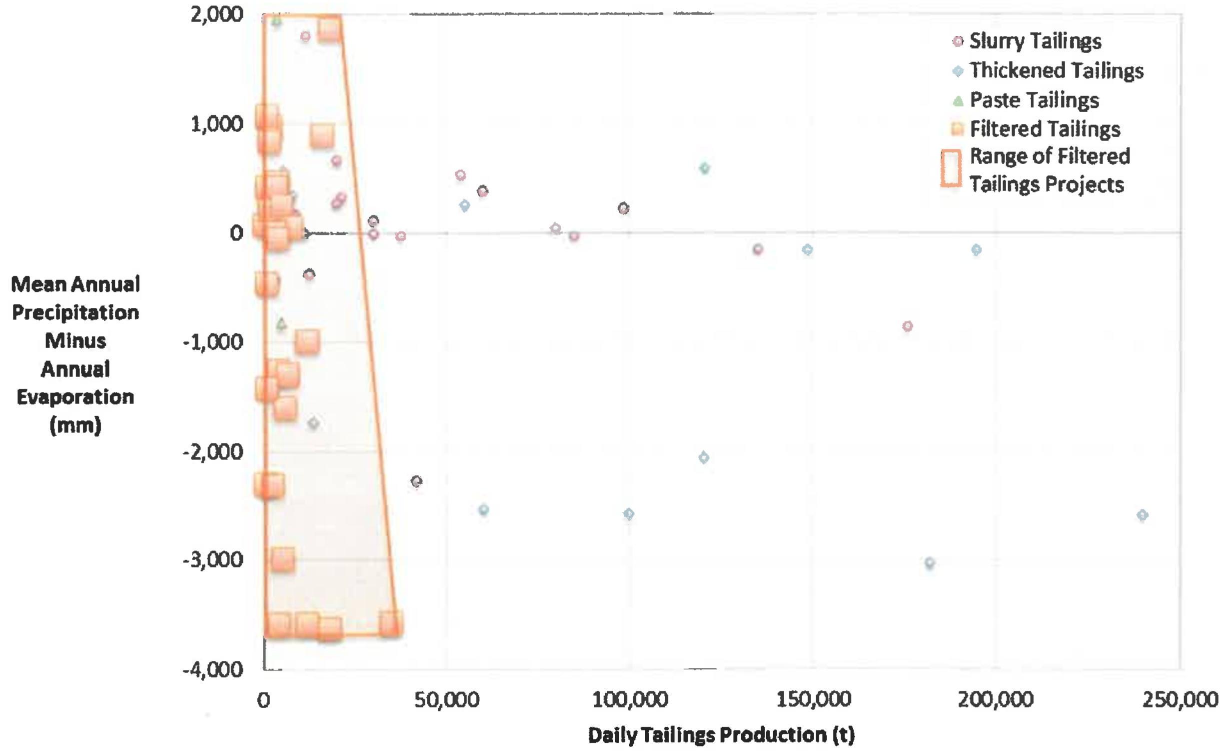
Notes:
Only facilities that are included in the case history review or provided a questionnaire response are included in the graph.

Figure 4.5 All Projects – Range of High-Density Thickened or Paste Tailings Applications (High-Density Thickened/Paste Facilities)



Note: only facilities that are included in the case history review or provided a questionnaire response are included in the graph. Range includes paste or high-density thickened tailings facilities, some of which are using paste deposition on the top of a conventional tailings facility to increase capacity.

Figure 4.6 All Projects – Range of Filtered Tailings Applications (Filtered Facilities)



Note: only facilities that are included in the case history review or provided a questionnaire response are included in the graph.

These plots show that unthickened and *thickened tailings* are managed across a wide spectrum of production rates (some more than 150,000 tpd) and climates (net positive and net negative water balances). In contrast, paste and filtered tailings have only been narrowly applied to-date, at less than 5,000 tpd for paste tailings and less than 35,000 tpd for filtered tailings (though the maximum operating tonnage has been approximately 20,000 tpd).

It should be noted that there are several projects in Australia and Chile that manage their tailings on the boundary of thickened and high-density thickened in high-density thickened/paste facilities at a range of production rates. Due to the extreme dry climate and temperatures of these locations being so different to Canada, these projects were not focused on in the plots in this section and not all of these projects are included.

4.3 General Lessons Learned from Case Studies

Some general lessons learned from the case studies are summarised in Table 4.2.

Table 4.2 Considerations for all Types of Tailings Facilities

Topic	Consideration
Segregation Technology	Particle segregation (e.g. sulphide flotation) and separate management of sulphidic ML/ARD tailings can be environmentally and economically beneficial, particularly if implemented at the start of mining. See Section 2.4.2.
Water Management	Safe water management at all tailings facilities is a major requirement for both water quality and physical stability of the facility. Tailings facilities should not accumulate water on a long-term basis and should have appropriate water discharge permits and, if required, water treatment plants, to allow discharge of water. Site design, catchment area, technology selection and progressive reclamation should also be considered to help manage the site-wide water balance.
Dust Management	Dust is a concern at all tailings facilities. Unthickened and thickened tailings allow the opportunity for continual wetting of exposed beach surface. Progressive reclamation of filtered piles provides an opportunity for reducing surface areas exposed to potential dusting, but areas that can't be reclaimed (e.g. large active deposition areas) may require active dust management.
Deposition	Placement of tailings in "exhausted" open pits and in underground workings can be a good tailings risk-reduction approach, both geotechnically and geochemically depending on the conditions.
Risk and Consequence of Failure	Risk is the key consideration when designing, constructing and operating a tailings facility. Tailings facilities should be designed to minimize the consequence of a potential failure as much as possible. For example, not using a tailings facility for long-term water storage for the mining operations.
Closure	Tailings facilities should be designed for dry closure with appropriate land and water use and/or landform transition. The potential risk cost associated with the tailings facility during long-term closure should be considered within the selection process for closure design (see Section 5.5).
Risk and Life-Cycle Costs	During tailings management planning, the full risk profile of alternative tailings management strategies (including life-cycle costs) should be considered. This can be done through a structured assessment, such as Failure Modes and Effects Assessment (FMEA). See Section 5.7.

5 KEY CONCEPTS FOR COMPARISON

5.1 Constructability

Constructability is a significant consideration in the design and operation of tailings facilities. In general, the earthworks and civil works required for most components have precedents and standardized procedures. Containment dams for slurry require attention (often over a long period of time), good dam design, good construction practices, and often need to include tightly specified materials such as filters and drains (which can be difficult and expensive to produce).

High-density thickened/paste and filtered tailings facilities, however, may also have significant constructability concerns for large-scale operations. Particularly, with respect to the very large, and mechanically complex conveyor transport systems and placement equipment fleets/areas. Operations in variable climatic conditions and in mountainous terrain also introduce significant construction and operational challenges and will require adequate back-up plans.

Predicting beach slopes for any kind of tailings is difficult, however, high-density thickened/paste tailings facilities that rely on achieving a certain beach slope may require substantially larger footprints than anticipated, or higher containment dams if the design beach slopes cannot be achieved consistently.

5.2 Water Management

Given what has been presented with respect to the general management of dewatered tailings technologies, a primary driver behind the selection of dewatered technology or facility type is the management of water, both quantity and quality. Water management is also an important factor as it influences the physical and geochemical stability of the tailings.

Mine sites are categorized as having either a net positive water balance (surplus) or net negative water balance (deficit). At sites with a net positive water balance, strategies generally involve reducing the amount of water by limiting the contributing watersheds (i.e. diversions) and with controlled release of water (treated, if required). Where a net negative water balance exists, strategies generally focus on conserving water by limiting *evaporation* losses and increasing dewatering in order to recover water to the ore processing facility. Evaporation losses can be minimized by limiting the wetted beach and pond area in the tailings facility.

Conventional tailings facilities usually provide storage for seasonal attenuation of runoff and flood routing. This additional storage capacity can be a considerable advantage over high-density thickened/paste or filtered tailings facilities, which require separate water management facilities.

Tailings dewatering usually transfers the management of a portion of the processing water from the tailings facility to the dewatering plant (which could be located at the ore processing plant).

Figure 5.1 illustrates the reduction in water recovered from the tailings facility with the range of dewatering technologies. For illustrative purposes, an initial solids content of 30% by weight is assumed to be produced at the ore processing facility. It is important to note that the solids content (i.e. density) of the initial settled tailings may not significantly change with the dewatering technology and that the main difference is the quantity of water that reports to the tailings facility (although compacted filtered tailings will achieve higher densities than conventional, thickened or paste tailings).

Table 5.1 summarizes where the water is typically stored, along with key water management concerns, for each type of facility.

Figure 5.1 Comparison of Water Recovery for Tailings Technologies

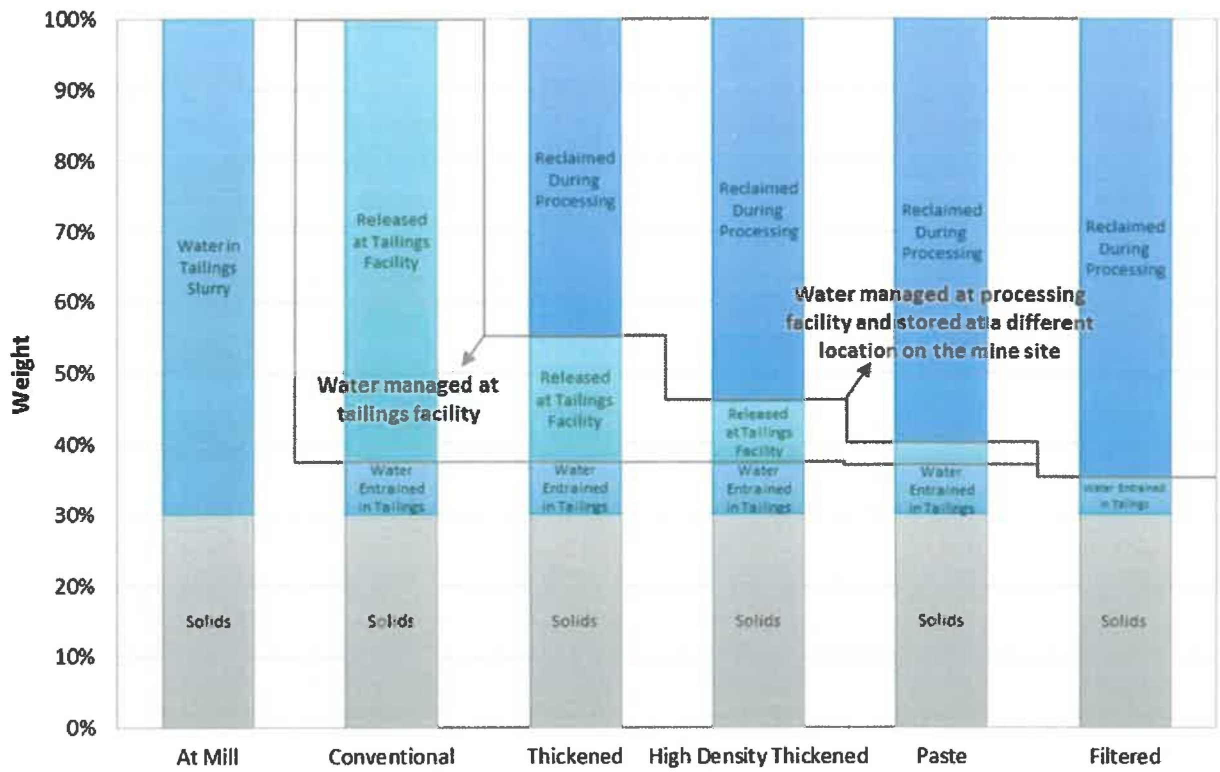


Table 5.1 Typical Water Storage and Water Quality Considerations for Different Types of Tailings Facilities

Type of Tailings Facility	Water Stored at Tailings Facility	Water Stored at a Separate Water Storage Facility	Water Management Concerns at Tailings Facility	Water Management Concerns at a Separate Storage Facility	Geochemical Management
Conventional (see Figure 3.1)	Majority of water	Not required	▪ Potential for catastrophic failure with mobilized tailings if pond volume is released.	▪ A separate water storage facility may be a risk reduction measure.	▪ Can limit sulphide ML/ARD and ML. ▪ Can increase non-sulphidic ML. ▪ Large volume of water to be treated if ML or ML/ARD occurs.
High-Density Thickened/Paste (see Figure 3.3)	Lower volume than conventional	Majority of water	▪ Potential to mobilize tailings somewhat reduced from the conventional case since pond water volume is usually minimal, but tailings are also deposited loose and saturated. ▪ Erosion control and sediment management.	▪ Operation of large external facilities. ▪ Consequence of failure of water management pond.	▪ Increased risk of sulphide ML/ARD and ML. ▪ Moderate risk of non-sulphidic ML. ▪ Increased risk of dusting from exposed tailings. ▪ Less volume of water to be treated if ML or ARD occurs.
Filtered (see Figure 3.5)	Minimal requirement	All water	▪ Erosion control and sediment management.	▪ Operation of (potentially large) external facilities. ▪ Consequence of failure of water management pond. ▪ Sediment management.	▪ Increased risk of sulphide ML/ARD and ML. ▪ Moderate risk of non-sulphidic ML. ▪ Increased risk of dusting from partially-saturated exposed tailings[1].

Notes:

1. Filtered tailings facilities might be suitable for progressive reclamation, which will decrease dusting, ML and ML/ARD risk in reclaimed areas.

5.3 Potential Mobilization of Stored Tailings

The potential mobility of *in-situ* tailings from a hypothetical dam breach is closely related to the amount of water stored in the facility (both free water and water contained in the voids) and the robustness of the containment design and the consequence of a containment (dam or slope) failure. Wind and precipitation can also result in the mobilization of tailings through dust and water erosion.

Amount of Water Stored in the Facility

The more water stored in a tailings facility, the more water that may be released during a hypothetical dam breach. The released free water will mobilize tailings and transport the tailings downstream. As described in Table 5.1, conventional facilities typically have the largest pond (free) water volume, and therefore, typically have the highest potential for mobilization and transportation of tailings and the highest consequence of failure. However, there are some considerations for thickened/paste and filtered facilities:

- Some high-density thickened/paste facilities store water against their containment dam, which increases the risk of releasing the pond and associated risk of mobilizing tailings.
- When large water ponds are located downstream of high-density thickened/paste or filtered facilities, cascading failures are possible and should be accounted for when developing the risk profile of tailings facility management.

Strength and Deformation Behaviour of Tailings

The strength of deposited tailings is controlled by saturation and density. Loose, saturated tailings have a greater likelihood of acting like a fluid in the event of a tailings dam breach or a liquefaction event. Unsaturated and/or dense tailings are less likely to act like a fluid during a dam breach and may experience limited *strain* under a liquefaction (cyclic mobility) event; unsaturated and/or dense tailings are likely to deform by slumping/settling, and impacts may be limited to areas in, and closer to, the facility.

High-density thickened/paste tailings can still be loose and saturated, therefore more susceptible to liquefaction, which can cause the tailings to flow downstream in the event of a dam breach.

All tailings dewatering technologies, except some filtered tailings processes, result in saturated tailings at the time of deposition. Filtered tailings can be placed saturated or partially-saturated (saturated less than 100%). If there is limited drainage, saturation of filtered tailings can occur at constant moisture content due to consolidation under self weight as the pile height increases. In dry climates, evaporation and seepage can combine to desaturate (decrease the saturation below 100%) a previously saturated tailings pile. Conversely, in a wet climate, filtered tailings, which start partially-saturated, can become saturated due to infiltration, hence, the goal of achieving a final tailings deposit that is unsaturated can be difficult to achieve in wet climates.

The effect of placed density on tailings' static and seismic stability is complex and requires special expertise to evaluate. Hydraulic and paste tailings will initially be loose, however *desiccation*, compaction (on wet or dry beaches), farming techniques and other methods can increase the density. Filtered tailings are usually compacted, at least in the important structural zones. These compaction techniques impart only a modest over-consolidation pressure to the tailings and this is quickly overcome as load is applied by the self-weight of the rising pile. As load increases, loose tailings consolidate and eventually reach the normally consolidated state, which is the state of saturated hydraulic or paste tailings when deposited. Below a depth of a few tens of metres, both compacted and uncompacted tailings reach similar densities, and can be expected to behave in a similar manner. The important feature of the normally consolidated state is that saturated tailings will normally be subject to loss of strength if *undrained loading* is triggered statically or dynamically. It is usually not possible to identify all triggers that can induce undrained loading, so a safe assumption is that triggering will occur and the facility needs to be stable under undrained peak and residual strength.

Sand tailings behaviour is more complex since sand behaviour is often based on density relative to the *critical state line*. Increase in load, as the pile height increases, causes the sand state to move towards the critical state density and, as *confining stress* increases, the sand becomes looser relative to the critical state (although denser in absolute terms).

In summary, at low stress, compacted material, will behave much more favourably than the same material at high stress. In the absence of a dam to contain the tailings, the stability of structures which rely on support from saturated tailings and are more than a few tens of metres high, need special attention.

Robustness of Containment Design

In the event of a dam breach, the amount of water and tailings released depends on the dam structure. If the design is robust or there are redundancies (secondary containment) in place within the impoundment, the quantity of water and tailings released can be minimized. Some examples of this include:

- Long tailings beaches with reclaim ponds located far from the dam crest decrease the likelihood of the pond being released during a slumping failure of the dam.
- Tailings facilities built in cells often have intermediate dykes that get built in to the final structure.
- Tailings dams constructed of rockfill and less erodible materials.
- Downstream containment structures (like collection ponds).

Dust and Progressive Reclamation

Tailings are more prone to dust generation when they are partially-saturated and exposed to wind. Dusting can be a major concern and is typically more challenging if:

1. The site is known to be windy.
2. There are large, exposed areas of tailings that have not been reclaimed.
3. The tailings "ball-up" under freezing conditions.
4. The tailings are not saturated (dry climates — even dry seasons, or if tailings are filtered).

Some types of tailings will form a crust which reduces the potential for wind erosion. Crust formation can be tested in wind tunnels. Generally, compacted tailings, saturated tailings and fine tailings are less prone to dust generation, however, sand — especially segregated beach sand — has a high potential for dust generation.

The first factor — a windy site — is independent of tailings dewatering technology or facility type, however, the other factors are not. Conventional facilities may have large areas exposed to wind prior to reclamation, however, in wet climates (most of Canada for part of the year) the tailings may stay saturated, or close to saturated, which helps reduce dust. Conversely, exposed tailings can freeze into small, sand-sized balls during the winter months and this can result in severe seasonal dusting.

High-density thickened/paste tailings may be more susceptible to dusting because of the large, un-reclaimed beach areas and more wind access (based on the geometry of these facilities). However, depending on the tailings properties, sometimes the tailings will form a protective crust.

Filtered tailings offer the most control on construction sequence and final geometry of the tailings facility. Therefore, progressive reclamation of the surface is often possible, which can reduce erosion and dust. Larger-scale operations using mobile stacking conveyors for transporting and placing filtered tailings, and facilities that are expanding outwards as well as upwards, require a large, active area for placement, and consequently are less suitable for progressive reclamation.

5.4 Water Quality

Managing the quality of water within and discharged from the facility (either through surface or groundwater) is as important as managing the quantity of water stored, discharged, and reclaimed from the facility. Water quality management is not only an important factor for regulatory compliance, it can also influence processing and mineral recovery when used as reclaim in the ore processing circuit.

Water quality is managed several ways at conventional tailings facilities:

- a wetted beach or pond to limit sulphide oxidation and metal leaching from sulphidic ML or ML/ARD tailings;
- a rotating schedule of tailings deposition to sequentially cover sulphidic ML and ML/ARD tailings — which may oxidize (or have oxidized) — with fresh tailings, and associated alkalinity from ore processing;
- the subaqueous, or underwater, deposition of high sulphide ML/ARD tailings;
- the treatment of water prior to discharge via passive or active treatment methods; or
- a combination of the approaches above.

Since most high-density thickened/paste and filtered tailings deposition (outside conventional facility configurations) is subaerial, the traditional water quality management strategies of limiting oxygen to the tailings through saturation are more difficult to employ. However, limiting contact water to the tailings through compaction or other strategies can be successful at reducing contact water volumes and the development of ML/ARD.

In summary, conventional tailings impoundments have some potential advantages over paste and filtered tailings facilities in terms of controlling the on-set of sulphidic ML/ARD by maintaining saturation, or submergence of tailings. However, the presence of a significant pond on the tailings surface comes at an increased risk due to the failure consequences associated with the potential release of the free water.

Other physical and geochemical controls can be used to improve the geochemical performance of tailings facilities, such as techniques that limit oxygen by placing a saturated and/or oxygen consuming cover (e.g. de-sulphurized tailings that maintain a groundwater level above the PAG tailings), sulphide segregation methods, and low permeability covers. Details of these approaches are provided in Appendix I.

Other water and tailings management practices that reduce the impact on water quality include limiting contact water, smaller footprints, and water treatment.

5.5 Closure and Long-Term Performance

All tailings facilities will require cover systems, instrumentation and long-term monitoring to assess physical stability. No examples of closed, high-density thickened/paste or filtered facilities were identified, and thus, there is little information on actual long-term performance of such facilities, although there is data from modelling of long-term performance.

Tailings are prone to settlement post-closure, and loosely placed tailings typically undergo greater settlement after deposition than compacted tailings. The looser the state on deposition, the more settlement can be expected, so slurry tailings would have much higher potential settlement than paste tailings. The settlement amount and rate can be predicted by laboratory testing, and it usually takes many years to substantially complete. This can significantly delay the time to reach a stable final surface for closure, especially for large conventional storage facilities.

Filtered tailings or cycloned sand that can be compacted on placement will experience much less post- closure settlement. Well desiccated/dry tailings are also less prone to large, post-closure settlements.

Trafficable tailings surfaces such as cycloned sand, well-drained/desiccated beaches, or filtered tailings provide better access for construct of cover systems, compared to fine, saturated tailings surfaces such as fine tailings deposited in topographic lows, or high-water-retaining paste tailings.

Even in the absence of significant ML or ML/ARD, process water entrained in tailings often needs to be collected and managed as it seeps out of the deposit. Eventually, after closure process water will be flushed out by precipitation. The volume of process water entrained in pore voids is largest in conventionally deposited tailings slurry, and lowest in filtered tailings. If dewatered and managed properly, filtered tailings facilities can have minimal seepage rates during operation and post-closure.

For long-term closure, soil covers are the preferred method of controlling infiltration rates and reducing geochemical impacts. All tailings deposits can theoretically be closed with soil covers (cost is potentially a limiting factor) and the covers can be designed to reduce infiltration and potentially reduce oxygen diffusion. A key to the success of the cover is providing long-term protection from erosion from rain and wind, and disturbance from animals and humans. It is more difficult to provide an erosion-resistant cover on a sloping surface, such as the perimeter of a filtered tailings facility, than on a flat surface, such as a conventional tailings facility.

5.6 Cost

Limited information on project specific life-cycle costs for tailings dewatering technologies is available in the public domain, and the information collected for this study's inventory is not sufficient to do an accurate comparison of the relative costs of these technologies and practices across the entire life-cycle, including construction and operational costs, closure and long-term (post-closure) costs. The industry's understanding of the entire life-cycle costs of these dewatering technologies and facility types has been identified as a knowledge gap and should be further studied.

Despite this, the main finding of this study is that there are no universally ideal tailings dewatering technologies or facility types. For a given project, the ideal solution will depend on the tailings properties, production scale, site characteristics and available technologies and facility types. For example, the cost of a particular technology/facility type will be vastly different for coarse, non-reactive tailings in a dry climate than it will be for fine, sulphidic ML/ARD tailings in a wet climate.

While it is not possible to provide definitive capital costs; operating cost estimates were obtained from the surveys, suppliers, literature search and KCB project experience based on broad assumptions, and therefore would not be applicable to every project. Indicative operating costs are presented in Table 5.2, that are based on the processing (dewatering, transportation and placement), dam and water management components summarized in Table 5.3.

Table 5.2 Typical Relative Operating Cost per tonne of Tailings Storage for Different Tailings Dewatering Technologies (capital and closure costs not included)

Dewatering Technology	Typical Processing & Transport Cost ($/t)	Typical Dam & Water Management Cost ($/t)	Typical Total ($/t)	Range of Cost ($/t)
Unthickened (conventional)	$0.20	$1.00	$1.20	$0.50 to $2.50
Thickened	$0.30	$1.00	$1.20	$0.50 to $2.50
High-density thickened	$0.50	$0.90	$1.50	$0.75 to $2.50
Paste	$1.50	$0.50	$2.00	$2.00 to $8.00
Filtered	$5.00	$0.20	$5.20	$4.00 to $12.00

Notes:

1. Costs are very site- and project-specific and the costs shown are only for indicative purposes to illustrate the relative range of costs for the different dewatering technologies.
2. Tailings cost per tonne typically decreases with larger tonnage operations due to economies of scale.
3. Capital and closure costs not included.

Table 5.3 Major Cost Items

		Facility Type		
		Conventional	Thickened/Paste	Filtered
Capital	Tailings Handling	Centrifugal pumps Tailings pipelines	Tailings thickeners *Vacuum filters (disc or belt)* *Positive displacement pumps* Tailings pipelines	Tailings thickeners *Vacuum or pressure filters* *Conveyor collection/handling system* *Haul trucks or mobile stacking conveyor system* *Compaction equipment (dozers, compactors)*
	Other	Starter tailings dams Seepage collection dam/ponds/reclaim Reclaim water system Water treatment plant Non-contact water management (diversions, wells, ponds)		*Starter facilities* *Seepage/runoff collection dam/pond* Water treatment plant Non-contact water management (diversions, wells, ponds)
Operating	Tailing Processing	Pumping energy Thickener operation (flocculants, energy)	*Thickener operation (flocculants, energy)* *Filtration energy* *Pumping energy*	Thickener operation (flocculants, energy) *Filtration energy* *Conveyor/truck operating cost* *Placement and compaction*
	Other Operating	Dam construction Deposition piping and relocations Make-up water Seepage pump back Water treatment	*Reclaim water*	Foundation preparation *Contact water management* *Dust management and erosion protection* *Progressive reclamation of tailings* Makeup water Water treatment (*depending on geochemical strategy*)
Closure		Dam reclamation Tailings surface reclamation and covers Ongoing water treatment (*depending on geochemical strategy and effectiveness of cover system*) Spillway(s) Infrastructure decommissioning Dam and spillway monitoring and maintenance		*Remaining tailings reclamation and covers* Ongoing water treatment (*depending on geochemical strategy and efficacy of cover system*) *Infrastructure decommissioning* Pile and water management features monitoring and maintenance

Note: Coloured text indicates items that are key differences compared to conventional facilities. Green text indicates items that are typically less expensive and red text indicates items that are typically more expensive in comparison with conventional facilities.

5.7 Risk

As introduced in Section 2 and discussed throughout this report, risk is a key consideration when deciding on a tailings management strategy. The optimum tailings technologies and facility type for a given project should be chosen to reduce the overall risk profile of the project, and will be specific to the tailings and site characteristics and should consider available technologies and the social/regulatory systems.

When assessing risk, the likelihood and consequence of failure are considered. However, even if the likelihood of a potential failure is estimated to be very low, the consequence of failure may be such that additional and significant risk mitigation measures are required.

At least one type of risk assessment should be completed for the project when deciding on the tailings management strategy and should be updated periodically. There are several different types of risk assessments or structures that could be used, such as:

- Multiple Accounts Analysis (MAA) – decision making tool that identifies tailings management strategies, eliminates unfeasible ones, characterises and ranks the remaining based on multiple accounts and value criteria (Robertson and Shaw 2004).
- Failure Modes Effects Assessment (FMEA) – used to identify potential failure modes and their respective likelihood and consequence to develop mitigation strategy and risk management plan (McLeod and Plewes 1999).
- Bowtie Risk Assessment – used to characterise high consequence events; widely used for describing causes and what controls are in place to try and prevent the event or mitigate the catastrophic outcome (Mills et al. 2016).
- Event Tree – used to estimate the probability of a failure; generally used in combination with another method (Fell et al. 2000).

6 SUMMARY AND COMPARISON OF DEWATERING TECHNOLOGIES

It is sometimes perceived that there is one tailings dewatering technology and facility type that is the best, however, this is not the case. There is not a universally *best* dewatering technology or facility type. The ideal technology and facility type for a given project will be specific to the tailings, production scale, site characteristics, available technologies and facility types and social and regulatory considerations as illustrated in Figure 2.1. Some technologies and approaches may provide greater geotechnical stability, others geochemical stability, and combined approaches may help address both.

This section summarizes the strengths, limitations, and physical and geochemical risks of the alternative facility types, compared to conventional tailings facilities (Table 6.1 and Table 6.2).

Table 6.1 Strengths and Limitations

Item	Conventional Tailings Facilities	High-Density Thickened/Paste Tailings Facilities	Filtered Tailings Facilities
Processing			
Strengths	▪ Technology can be widely applied to different types of ore/tailings. Equipment is widely available and processes are well known.	▪ Advances are being made in the industry in terms of ease of operation and scalability.	
Limitations	▪ For cycloned sand facilities, it may require two-stage dewatering to achieve the required sand fraction. ▪ Cycloning is not applicable to projects where the tailings sand content is below about 30%.	▪ High-density thickeners and filters required for dewatering require more operational attention and are subject to system "upsets" from ore variability, gradation, or operator attention. ▪ It could take months or years to optimize the thickening system to produce a consistent tailings product and the achieved solids contents are often at least 5% lower than the design target. ▪ Paste tailings can require both thickening and filtering. ▪ Increased processing costs.	▪ Cannot be widely applied to all tailings/ore types (fine and clayey tailings are challenging to filter to low moisture contents). ▪ Filters or filter plants require more operational attention and are subject to system "upsets" from ore variability, gradation, or operator attention. ▪ Filtered tailings may require additional pre- and post-processing to achieve desired moisture contents, such as thickening prior to filtration or reworking of tailings ("farming") post deposition. ▪ Ability to achieve desired moisture contents are difficult and may require mitigation during operations (which can reduce throughput and slow production). ▪ Separate ponds or tanks are required to store filtrate water prior to re-use. ▪ Covered sheds or additional storage ponds are required in the case of system upset when filtering must stop. ▪ Increased power usage and processing costs.
Transportation			
Strengths	▪ Hydraulic placement allows for transportation over long distances at relatively low capital and operating costs.	▪ Locating dewatering plants strategically, (higher elevation and close to the tailings facility) can decrease transportation costs.	▪ Locating dewatering plants strategically, (higher elevation and close to the tailings facility) can decrease transportation costs. ▪ Truck/conveyor transportation allows more control over placement location and, therefore, final pile arrangement.

Item	Conventional Tailings Facilities	High-Density Thickened/Paste Tailings Facilities	Filtered Tailings Facilities
Limitations	▪ Secondary containment of pipelines can add costs. ▪ For cycloned sand, the coarse underflow with a high solids content can be difficult to transport over long distances.	▪ Positive displacement pumps may be required for transportation. ▪ Increased risk of plugging pipelines with high-density materials. ▪ Transportation costs can be higher due to increased energy required for pumping.	▪ Trafficability of filtered tailings surfaces can be a challenge depending on tailings type, moisture contents from the filter plant and climate conditions. ▪ Conveyor and truck operations can be challenging in cold and wet climates. ▪ Conveyor operations are limited to simple facility configurations. ▪ Higher transportation costs due to power (for conveyor), fuel, and labour.
Deposition			
Strengths	▪ Tailings naturally consolidate to the similar in-situ density as high-density thickened/paste. ▪ Natural segregation of particle sizes in the tailings beaches (where coarser tailings are at the dam edge) and the lower phreatic surface in the beach (or cycloned sand dam) improves dam stability. ▪ Cycloned sand dam construction decreases the amount of borrow required for dam construction. ▪ Construction of cycloned sand dams are not sensitive to high rainfall.	▪ In theory, may achieve steeper tailings beach slopes to reduce perimeter dam heights. The lower dam heights can reduce capital costs. ▪ Minimal particle size segregation after placement resulting in a consistent hydraulic conductivity and higher moisture retention capacity, which can aid in ML/ARD control. ▪ Tailings can also be used as underground backfill.	▪ Partially-saturated tailings product allows for more control when handling. ▪ Can save on starter facility or dam construction capital costs as the facility is constructed out of the tailings themselves. ▪ Can increase the capacity of an existing conventional facility by stacking on top. ▪ May permit storage in areas with steep topography or where a conventional dam is impractical. ▪ Compaction can be done with conventional earthworks equipment. ▪ More control over ultimate pile configuration.
Limitations	▪ Deposition method often results in large beach areas, which have variable properties and can be difficult to control. ▪ Dams are required to contain the tailings, which may require borrow material. ▪ Beach slopes are generally less than 1.0%.	▪ Beach slopes are difficult to predict and will vary depending on operational practices, tailings properties, and weather. Beach slopes are typically < 1.5 %. ▪ Dams are required to contain the tailings, which may require borrow material – dams may be lower than for conventional tailings facilities ▪ Significant drying time (if required) is often not achieved in wet climates and required rotation of the discharge point.	▪ More challenging in wet and cold climates. ▪ Deposition by conveyor or truck and shovel can be difficult to scale to higher tonnage rates. ▪ Still require "structural zones" for containment, which act like dams, made of compacted tailings. ▪ Increased potential for dust generation. ▪ Erosion control can be difficult. ▪ Over-wet tailings must dry prior to compaction (which is required for stability and trafficability). ▪ High rainfall areas typically require rockfill roads within the facility, which may increase the external borrow requirements if waste rock is not available.

Item	Conventional Tailings Facilities	High-Density Thickened/Paste Tailings Facilities	Filtered Tailings Facilities
			▪ Adds complexity to operations. ▪ Need a separate area to deposit wet or sloppy tailings from process upset conditions.
Water Management			
Strengths	▪ Greater operational flexibility for overall mine water management (including seasonal variability). ▪ Provides a pond for subaqueous deposition of sulphidic tailings.	▪ Reduced water volumes to be managed in the tailings facility. ▪ Tailings can have a higher water retention capacity to promote saturation and help limit sulphidic ML and ML/ARD. ▪ Small to no ponds on the tailings surface.	▪ Beneficial in northern environments where tailings freezing occurs because of water in the tailings. Filtered tailings will not freeze because they are partially-saturated. ▪ High water recovery within the process plant for reclaim use.
Limitations	▪ Water management must be balanced as not to store too much water in the facility while allowing for contingency storage for shut down periods, excess site water routed through the tailings, and other system upset. ▪ Higher volume of water to be managed at the tailings facility. ▪ Water storage is a key consideration in risk management (see Table 6.2).	▪ Typically, tailings facility does not provide adequate storage to attenuate seasonal flows. Therefore, requires external water storage to effectively manage runoff and other site water. ▪ Precipitation and wind on slopes can lead to increased erosion. However, some tailings may form a crust that will decrease the susceptibility to dusting.	▪ Requires external water storage to effectively manage runoff and other site water. ▪ Precipitation and wind on slopes can lead to increased erosion. However, some filtered tailings facilities can be staged for progressive reclamation that will help control erosion. Compaction can also be use to decrease susceptibility of the tailings to dusting.
Closure			
Strengths	▪ Several decades of case studies, research, and precedents on closure measures. ▪ If designed appropriately, can be closed as a "dry" facility.	▪ Closure cover placement and trafficability is easier than on conventional tailings facilities. ▪ If designed appropriately, can be closed as a "dry" facility.	▪ Smaller operations and smaller footprints are easier to construct and to maintain design integrity of closure measures. ▪ Progressive reclamation may be possible depending on the design. ▪ Amenable to dry closure and landform development.
Limitations	▪ Soft tailings and slimes can take a long time to become trafficable to implement closure measures. ▪ Progressive reclamation is difficult. ▪ Typically, takes a relatively long time to drain-down and, therefore, requires long-term seepage management.	▪ Little to no precedents for closure implementation. ▪ Large area cone depositions can be costly to close. ▪ Progressive reclamation is difficult.	▪ No precedents for closure. ▪ Difficult implementation of source control measures for closure of sulphidic ML and ML/ARD facilities.

Item	Conventional Tailings Facilities	High-Density Thickened/Paste Tailings Facilities	Filtered Tailings Facilities
Precedents			
	▪ Precedent for failures (WISE-Uranium 2017). ▪ Public documentation on the design, risks and performance of high dams would be of benefit. Limited information is available on high embankments (current reported maximum centreline height for a sand dam is approximately 200 m – Quillayes Dam (Barrera et al. 2011), although the current overall slope height is closer to 250 m). Higher dams are being proposed and could be anticipated to range over 300 m high. ▪ The upstream tailings dam methodology continues to be applied at many mines in Canada. Such structures typically have a larger degree of uncertainty and risk with respect to the dam material geotechnical properties. Consolidating available information on tailings in-situ properties would be of benefit to help the industry understand the practical limits to these facilities.	▪ There is limited precedents for thickened/paste tailings facilities, which include the following considerations: ♦ The effectiveness of controlling ML/ARD over a large exposed tailings slope. ♦ Maintaining target slope angles. ♦ Managing storm water (storage and erosion).	▪ There is a lack of precedents for filtered tailings facilities at large scales, which include the following considerations: ♦ Current filtered tailings operations in Canada use trucks to transport the tailings to the facility. However, larger scale operations typically use conveyors and mobile stacking equipment. The operation of this equipment in winter environments and the ability to control downtime and equipment upsets due to blizzard and extreme conditions is uncertain. ♦ Large, filtered piles typically require compaction of a structural zone to mitigate the potential for a flow slide (initiated by either static or seismic loading). Further review of compaction requirements and limitations of compaction due to wet and cold conditions would be beneficial. Factors that influence the degree of saturation of the tailings should be considered. ♦ The clay content and plasticity of the tailings directly influence the efficiency of dewatering equipment and further research on linking the tailings properties to the feasibility of dewatering would be beneficial. For example, if the effectiveness and requirements of certain dewatering technologies could be estimated based on tailings properties, this would help during the planning stages. ♦ Large tonnage, filtered tailings operations require a significant number of filtration units (perhaps hundreds of separate units). To date, the operational logistics of such facilities have only been tested up to 20,000 tpd and in arid environments. ♦ Large tonnage operations could require filtered piles that are hundreds of meters high (current report maximum thickness is 70 m – La Coipa (AMEC 2008)). Research into the influence of compaction and construction variability on the deformation and stability of such piles would be beneficial.

Table 6.2 Physical and Geochemical Risks

Item	Conventional Tailings Facilities (including cycloned sand dams)	High-Density Thickened/Paste Tailings Facilities	Filtered Tailings Facilities
Physical Risks	▪ **Highest during operations.** ▪ Reclaim pond in tailings facility during operations increases the consequence and likelihood of failure. ▪ Loose, saturated tailings have potential for mobility especially if pond water is released by a failure.	▪ **Highest during operations and closure.** ▪ Still requires some management of water on tailings surface. ▪ Tailings have potential for mobility (not compacted) and are not fully contained by a dam in the event of structural failure. ▪ Little precedents for large scale operations.	▪ Risk of not being able to consistently meet material specifications during construction, which increases the likelihood of slope failures. ▪ No precedents for large scale operations.
Geochemical Risks	▪ **Highest during operations and closure.** ▪ Where the tailings are sulphidic, oxidation and runoff or seepage through these pervious zones may result in ML or ML/ARD. However, there are case study comparisons (precedents) for successful management of ML/ARD. ▪ In a suitable climate, the ability to saturate the tailings to manage ARD is a key advantage of this disposal method. However, if tailings are not managed appropriately and ML or ML/ARD occur, more water management will be required.	▪ **Highest during operations and closure.** ▪ Small-scale operations can be successful and control ML/ARD with no ponded water, but large-scale operations have a higher risk of ML/ARD in comparison to conventional tailings facilities.	▪ **Highest during operations.** ▪ Partially-saturated tailings containing sulphides will oxidize and generate ML/ARD. However, effective compacting, staging and progressive reclamation (when possible) can help control ML/ARD and limit active water management. ▪ Large-scale operations have a higher risk of ML/ARD in comparison to small- scale operations or conventional tailings facilities due to placement methods.

Table 6.3 presents a generalized assessment of the practicality of dewatering technologies based on tailings' physical characteristics.

Table 6.3 General Assessment of Dewatering Technologies by Tailings Physical Classification (see Table 2.2)

<table>
<tr><th rowspan="2">Facility Type</th><th colspan="5">Physical Tailings Characterization</th></tr>
<tr><th>Coarse Tailings (CT)</th><th>Hard Rock Tailings (HRT)</th><th>Altered Rock Tailings (ART)</th><th>Fine Tailings (FT)</th><th>Ultra-fine Tailings (UFT)</th></tr>
<tr><td>Conventional or Thickened Slurry</td><td colspan="4">Conventional or thickened slurry tailings are widely applicable to tailings types and gradations because there is little physical change applied to the tailings prior to deposition. Dewatering to the upper limit on this tailings classification is not limited by gradation.</td><td>Ultra fine tailings are more challenging but applicable to conventional or thickened slurry.</td></tr>
<tr><td>High-Density Thickened / Paste</td><td colspan="2" rowspan="2">Dewatering technologies are largely applicable to coarse tailings, although may not be necessary for very coarse tailings, because these tailings will drain rapidly after placement.</td><td rowspan="2">Dewatering takes more energy and the results are less consistent for finer tailings.</td><td colspan="2" rowspan="2">The water retaining capacity of fine tailings makes dewatering to a paste or filtered state difficult to achieve. It is generally more costly, energy intensive, and can yield inconsistent results. There are several Alumina operations that filter bauxite residue (red mud) at small production rates, however, they do not dewater to the optimum moisture content.</td></tr>
<tr><td>Filtered</td></tr>
</table>

Red – Low applicability
Yellow – Moderate applicability
Green – High applicability

Assessing tailings technologies based on the tailings' geochemical characterization is challenging, as it is dependent on (a) the geochemical behaviour of the tailings and the resultant leachate/seepage, (b) the site conditions, and (c) the water management and treatment required or employed by the operation. Table 6.4 presents a generalized assessment of the practicality of dewatering technologies based on tailings' geochemical characteristics.

Table 6.4 General Assessment of Dewatering Technologies by Tailings Geochemical Characterization

<table>
<tr><th rowspan="2">Facility Type</th><th colspan="4">Geochemical Tailings Characterization</th></tr>
<tr><th>Sulphidic ML/ARD</th><th>Sulphidic ML</th><th>Non-Sulphidic ML</th><th>Low Reactivity</th></tr>
<tr><td>Conventional or Thickened Slurry</td><td colspan="2">Sulphidic tailings, whether ML or ML/ARD generating, can be managed in a conventional facility by maintaining saturation (limiting oxidation). This approach is not always applied in a conventional facility; however, the geochemical control options are more widely studied and available.</td><td>Not ideal because of the larger volume of contact water.</td><td rowspan="3">By definition low reactivity tailings do not leach metal(loid)s or non-metals above regulatory limits and therefore are no different for the facility types.</td></tr>
<tr><td>High-Density Thickened / Paste</td><td colspan="2">If managed in a conventional facility, the same as above applies. The management in a central cone configuration is difficult for maintaining saturation, and increases the contact surface area for oxidation. High-density thickened or paste tailings might have more water retaining capacity but will have larger partially-saturated surface areas near surface in the facility for sulphide oxidation.</td><td>Can be managed in a smaller conventional facility but will have an increased contact water for dissolution if in a large central cone facility.</td></tr>
<tr><td>Filtered</td><td colspan="2">A smaller footprint, if achieved, is advantageous for water treatment volumes. Compaction of filtered tailings reduces infiltration and limits contact water. A partially-saturated zone near surface is likely to occur where sulphide oxidation is possible during construction/operation and at closure.</td><td>Limits contact water for dissolution reactions in the tailings.</td></tr>
</table>

7 KNOWLEDGE GAPS

This section outlines the key knowledge gaps that were identified throughout the study. A portion of the knowledge gaps are due to constraints that the industry has in sharing information and lessons learned.

The key knowledge gaps and subsequent recommendations for further study have been organized into four categories: costs, closure, other technologies, and geochemistry.

Costs

- There is a lack of publicly available information on the cost of tailings management, from construction to closure and post-closure. Compilation of a structured database of costs would assist in communicating the life-cycle cost of tailings management and aid in future tailings management decision making.
- If more research or studies are completed on life-cycle costs of tailings, all aspects of tailings management should be considered when developing the costs, not just those directly related to tailings deposition. For example, the list below includes some of the aspects, but is not exhaustive:
  - costs over design, construction, operations, closure and post-closure;
  - a contingency for temporary closure should be included;
  - processing facilities (dewatering plants, cyclones, etc.);
  - earthworks (machinery) and transportation (pipelines, conveyors, trucks);
  - water management (diversions, collection ditches, collection dams and ponds, piping, pumping);
  - geochemical management (additives, treatments);
  - progressive and final closure (covers, decommissioning of facilities);
  - maintenance (during all stages into perpetuity); and
  - instrumentation and monitoring programs.
- Life-cycle costs of tailings facilities generally address construction, operations, closure and post-closure. However, at the planning stage the closure plans are not comprehensively developed, and closure requirements can change over the life of the mine. Additionally, the comparison of alternative designs and alternative closure scenarios may not specifically address the potential risk-profile of each alternative. Developing a structured risk-profile for tailings management alternatives would be beneficial in identifying acceptable/unacceptable risks and deciding on the preferred management strategy.

Closure

- Compilation of closure case histories for all types of tailings facilities would be beneficial. The performance and monitoring of dry covers is very important in geochemical management given the desire to close facilities without ponded water.
- An important objective for tailings facilities is to, over time, transition the facility into a natural-like *landform* or a sustainable land/water use facility. Further research into what features may be required or incorporated into the facility design, such that it could be eventually classified as a landform, and further definition of criteria for a landform, would be beneficial.
- Further research on the long-term potential mobility of tailings would be beneficial for tailings planners to understand the long-term risks and to help design to minimize those risks.

Other Technologies

- Sulphide flotation can help manage geochemical risks by reducing the sulphide content of most tailings and allowing for separate management of the smaller volume of the concentrated sulphide stream. Continued research into other processing methodologies that work towards reducing the concentration of metals and contaminants of concern in the tailings would be beneficial.
- Unconventional dewatering technologies are being researched but are not commercially in use because of cost (e.g. centrifuges). Cost and scalability of filtering tailings is also one of the deterrents for mining companies. More research into decreasing costs and improving scalability (not just in processing, but during construction as well) of dewatering technologies would be beneficial.

Geochemistry

- There are unknowns around the effects of tailings ageing in conventional and dewatered facilities on long-term permeability, geotechnical stability, saturation and ML, ML/ARD, etc. There are also unknowns around the effects of seepage chemistry on tailings in dewatered facilities. Further research and long-term monitoring of tailings facilities should be completed to better understand these effects and appropriately design for and manage them.
- More research would be beneficial on the use of amendments or compaction as a ML/ARD control (or permeability control). Compaction can minimize water and oxygen infiltration. The effectiveness of this will likely be dependent on the tailings properties.

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APPENDIX I

Tailings Technologies

Appendix I
Tailings Technologies

I-1 GENERAL

This appendix provides in-depth details of various tailings processing technologies:

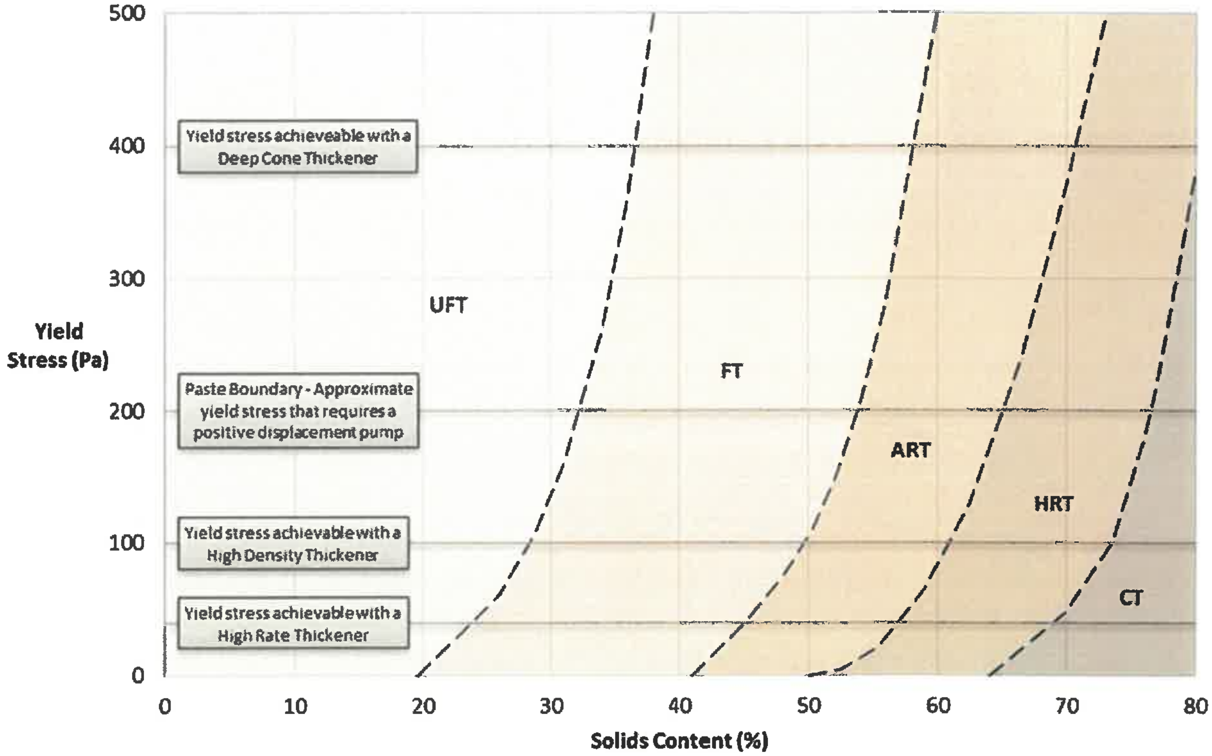
- Tailings Dewatering:
  - thickened
  - high-density thickened
  - paste
  - filtered (also known as "dry" stack or filter cake)
- Particle Segregation:
  - segregation during flotation
  - cyclones
- Sulphide Flotation:
  - segregation during plant flotation
  - sulphide flotation tanks
- Other Storage Technologies:
  - sub-aqueous tailings deposition
  - in-pit and underground tailings storage
  - tailings and waste rock co-deposition

I-2 TAILINGS DEWATERING

I-2.1 General

The continuum of dewatering tailings technologies is shown schematically in Figure 1.1 of the main text. Each dewatered state is loosely defined by its yield strength or stress (the applied stress that must be exceeded in order to make a fluid flow). Rheology, the study of the deformation and flow of matter, is an important consideration in tailings flow characterization, both for pipeline and pump sizing, as well as indicating the type and design of thickeners and filters that may be required. Rheology is characterised by two parameters — viscosity and yield stress. Both vary with solids content and specific gravity. Each tailings has a unique relationship between solids content and yield stress. Figure I-1 indicates the range of yield stress for various types of tailings, and the typical limits of dewatering. Filtered tailings (also known as filter cake, or dry stack) describes the tailings state after sufficient water has been removed, such that the tailings no longer behave as a fluid. A summary of dewatering processing technologies is presented in Table I-1 and described further in this section.

Figure I-1 Typical Yield Stress Achievable by Thickener Technology and Tailings Type (ICOLD 2017)



Hydraulically deposited tailings (conventional and thickened) are susceptible to earthquake-induced liquefaction if they are not adequately compacted. As a result, tailings facilities in areas of high seismicity are typically designed with downstream- or centreline-constructed dams. Similarly, filtered tailings can be subject to seismic liquefaction if they become saturated and are not compacted.

Table I-1 Summary of Tailings Dewatering Process Technologies

Dewatered Tailings Type	Process Equipment	Yield Stress Range (Pa)	Typical Solids Content at Deposition for Hard Rock Tailings[1,2]	Transport Method	Segregation (Low, Medium, High)	Degree of Saturation during Transportation	Typical Facility Type[5]	Typical Solids Content In-Situ for Hard Rock Tailings[1,2]	Typical Beach Slopes %
Unthickened	Product of the processing plant with no additional dewatering effort	<10	20% to 40%	Pipeline and centrifugal pumps	High	100%	Conventional	76%	0.5%-1%
Thickened	Flocculants and Conventional Thickeners or High Rate Thickeners	<30	40% to 60%	Pipeline and centrifugal pumps	High	100%		77%	0.5%-1.5%
High-Density Thickened	Flocculants and High-Density Thickeners (or High Compression Thickener) or Deep Cone Thickeners	<200 (ranges between 100 and 300)	60% to 70%	Pipeline and centrifugal pumps	Medium	100%	Thickened/ Paste	78%	0.5%-2%[3]
Paste	Flocculants and Deep Cone Thickeners or a combination of thickeners and filters	>200 (ranges between 100 and 300)	70% to 75%	Pipeline and positive displacement pumps	Low	100%		79%	< 2%[3]
Filtered	Filter (either vacuum or pressure)	n/a	>75%	Truck or conveyor	Low	< 95%	Filtered	83%	n/a

Notes:
1. Solids content is defined as the ratio of the weight of the tailings solids to the total combined weight of solids and water, Ws/(Ws+Ww).
2. Solids content relationship to yield stress varies depending on tailings properties, see Figure I-1. Typical values in this table are given for Hard Rock Tailings (HRT). HRT properties are further described in Section 2.2.
3. Steeper beach slopes of high-density and paste tailings are typically limited to a beach length of < 500 m. Longer beach lengths typically result in flatter beach slopes.
4. Process technologies including classification and segregation are not included in this table as they are a subset of all of the dewatered tailings technologies.
5. See Section 3 of the main text for descriptions of facility type.

I-2.2 Thickeners

Thickeners have been standard practice for many operations and designs have advanced over the past 20 years, simultaneous with advances in flocculant chemistry that improve settling rates (Jewell and Fourie 2015). Nonetheless, in practice the efficiency of thickening tailings to a very high solids content (e.g. > 60% for hard rock tailings) is difficult to achieve consistently, and solid densities during operations are often 3% to 5% less than the designed-for values. This is due to variability in grinding of the ore, mineralogy, and operator limitations. It is common for designs to be overly optimistic in this aspect, and past experience should be considered in the design of future thickened tailings projects.

The main objective of a thickener is to increase the solids concentration in the underflow (the heavier, coarser and free draining sand that is produced at the apex of a cyclone). The inflow (the material to be dewatered that is fed into the thickener) is a slurry with a low solids content. The solids are concentrated by gravity through the free settling phase, then hindered settling, and finally through compression settling; the thickened underflow is discharged through the bottom of the thickener and the clarified overflow water is released at the top of the tank. Rakes are commonly used in thickeners; these move radially and assist in moving the solids to the underflow discharge point.

The main factors that affect the thickening process are (a) solid-liquid weight ratio in the feed, (b) size distribution and shape of the solids particles, (c) clay content, (d) specific gravity difference between liquid and solids, (e) presence of flocculants, (f) viscosity of the liquor, (g) temperature, (h) method of flocculant application, (i) particle wetting characteristics, and (j) the movement of the particles mechanically (Jewell and Fourie 2015).

There are three main designs of thickeners (terminology varies throughout literature):

1. Conventional Thickener;
2. High Rate Thickener or High Capacity Thickener; and
3. High-Density Thickener, High Compression Thickener or Deep-Cone Thickener (also known as a paste thickener).

Wall height and the slope of the floor vary between thickener designs. Each design produces an increasing tailings solids content, as summarized below.

Conventional Thickener

Conventional thickeners have two different rake driving mechanisms: central drive and peripheral drive. Peripheral drive rakes have a central column that is used as a pivot point for the rotating raking arm that extends towards the periphery of the tank where it runs on a track.

Central drive rakes can be either a bridge- or column-type. The bridge-type includes a structure that spans across the thickener tank. The structure takes the vertical force of the mechanism, the accumulated solids and the horizontal force from the weight of the raked underflow.

High Rate or High Capacity Thickener

High rate thickeners have a configuration similar to conventional thickeners, but are designed to improve the throughput through better use of flocculants, control of base slope, and optimization of the interaction between the solids entering the thickener, the rate at which they settle, and the flocculant additives. Understanding these interactions allows the operator to control flocculants and the feed dilution to optimize the throughput and efficiency of the thickener (Jewell and Fourie 2015).

Slurry and flocculants are added to the thickener through an opening called the feedwell, which performs two important functions: dissipating the inflow across the area of the thickener and acting as the mixing tank for the addition of flocculants. The advancements of feedwell design enabled more efficient use of flocculants.

Figure I-2 High Rate Thickeners

Image reference: (Vietti Slurrytec 2015)

High-Density Thickener or High Compression Thickener

High-density thickeners and high compression thickeners are designed to achieve underflow with a higher solids content, along with several other attributes — high yield stresses, non-segregating behavior and release of less water after placement in a tailings facility. The thickener has several design features that enable this including: (a) maximizing the flux efficiency, (b) flocculant choice, (c) feed dilution systems, (d) deep tanks for increased compression, (e) longer residence times, (f) angling the bed of the tank (30° to 45°), (g) high torque rakes, (h) elevation of rakes, and (i) instrumentation and controls on flocculant dosage, solids inventory and underflow density (Jewell and Fourie 2015).

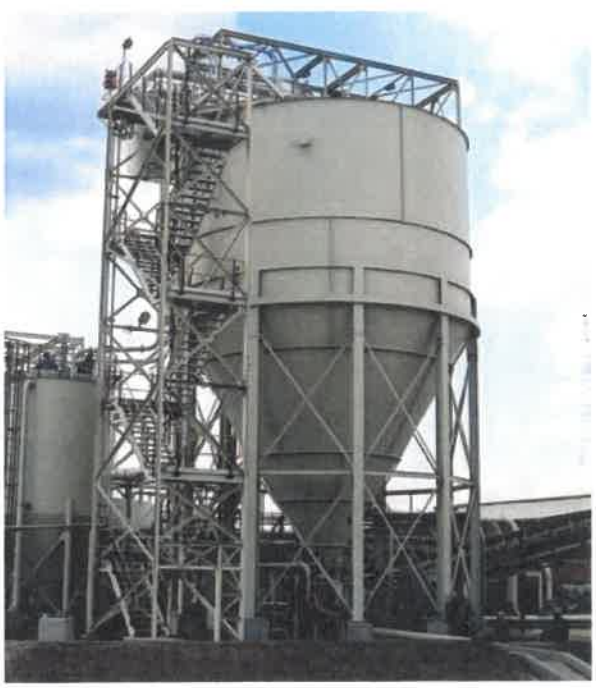
Deep Cone (or Paste) Thickeners

Deep cone thickeners were first developed in the 1990s. They have a much higher depth to diameter ratio than high rate thickeners, and have a steeply sloping floor. The depth of the solids bed is also greater, resulting in higher compression of the underflow. These thickeners differ from high-density thickeners in their wall height and slope of the thickener tank floor. Recent research indicates that control of the depth of the solids bed is key to producing a consistently high-density underflow. Densities of up to 70% solids by mass can be achieved, with the resulting underflow being a non-Newtonian (does not act like water) and non-segregating paste. An ultra-high rate thickener is shown in Figure I-3.

The application of Deep Cone Thickeners to surface tailings storage facilities has the following challenges:

- difficulty in achieving the desired density consistently;
- higher capital and operating costs than other thickener processes;
- higher mechanical and operating complexity and reagent cost; and
- when a higher density is achieved, positive displacement pumps may be required for transport of the tailings.

Figure I-3 Ultra High Rate Thickener (Deep Cone Paste Thickener) (EIMCO E-CM™ - Jewell and Fourie 2015)



I-2.2.1 Filters

As filters are less efficient at removing excess water than thickeners, thickeners are typically used to dewater the tailings to approximately 50% to 60% solids before the filtration stage. Filtration further dewaters the tailings, typically to 75% to 90% solids by weight. The required cycle time for filters, and thus capacity of a filter plant, depends on the following variables:

- Throughput
- Tailings Properties:
  - particle size distribution
  - clay and secondary mineral content
  - inflow solids content
- Tailings Target Moisture Content
- Water Chemistry
- Equipment:
  - size and capacity
  - cake thickness
  - filter medium
  - cycle time (for batch processes)

There are two primary types of filters used for tailings dewatering:

1. Vacuum filters use vacuum pressure to draw moisture from material through a filter membrane; and
2. Pressure filters squeeze the material between filter membranes, forcing water from the material.

Vacuum Filters

Vacuum filters include drum, disc or horizontal belt filters. Vacuum belt filters are less expensive to operate but typically cannot reduce the water content sufficiently for compaction. Their use, therefore, is generally limited to coarser tailings, dry climates (where air drying of the placed tailings further reduces the moisture content after placement), and low seismic risk regions. A vacuum belt filter is shown in Figure I-4.

Figure I-4 Vacuum Belt Filter

Image reference: (FLSmidth 2014)

Pressure Filters

Pressure filters include plate filters or pressure belt filters and can apply high pressure to achieve the necessary minimum moisture content. They are more costly and energy intensive to operate, however, and operate in a batch-process mode rather than as a continuous process. A typical cycle includes filling, pressure filtration (squeezing water out), potentially air blowing (decreasing saturation by blowing air through the material), discharging, and cleaning. A pressure filter is shown in Figure I-5.

Figure I-5 Vertical Plate Pressure Filter

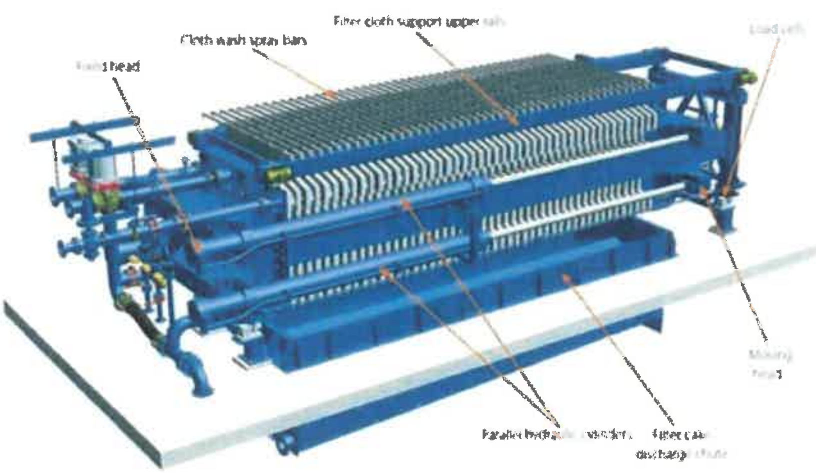


Figure 1: Vertical Plate Pressure Filter

Image reference: (CERIG 2013)

I-3 TAILINGS CLASSIFICATION AND SEGREGATION

Tailings classification and segregation are technologies that can be used in conjunction with the thickening and dewatering technologies.

Particle segregation could occur as follows:

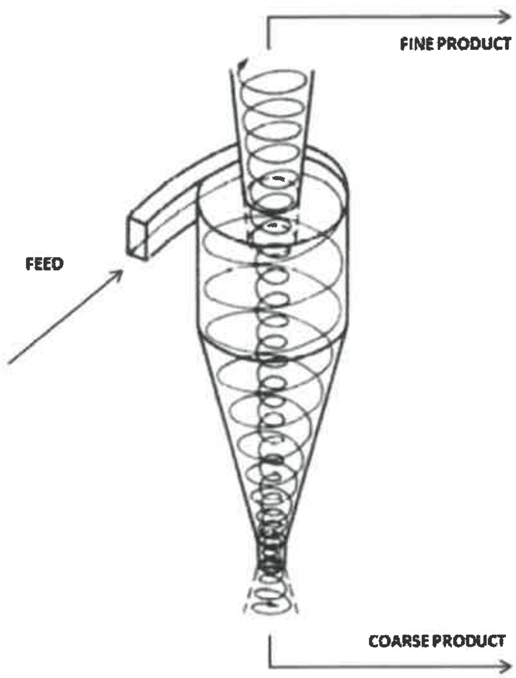
- In many porphyry copper and massive sulphide base metal mines, the flotation process may produce lower-sulphide, coarse scavenger tailings and higher-sulphide, fine, cleaner tailings products.
- Separate handling of these tailings streams allows different deposition methods. Typically, subaqueous deposition of the higher-sulphide, cleaner tailings is considered.
- There are several mines where the coarse cyclone underflow is dewatered using horizontal belt vacuum filters, or vibratory screens, for tailings deposition in dumps. The finer overflow tailings are thickened and pumped to a separate tailings storage facility. This method has been used in arid regions of Chile, where water recovery is the main driver.

Tailings Classification

Hydro-cycloning (or cycloning) of tailings is commonly used to produce coarse sand that is used for dam construction. The use of cycloned sand for dam construction reduces the requirement of external borrow sources (and resulting land disturbance) and reduces the quantity of tailings to be stored in the facility. Cycloning is most commonly used for large-scale porphyry copper applications. The relatively coarser-grind and the scale of the operations of hydro-cycloning requires a large storage area and a large amount of construction material.

Cyclones use centrifugal acceleration forces to separate particles based on size and specific gravity. The tailing slurry is fed into the cyclone; a typical schematic is shown in Figure I-6. The finer material is carried out with the majority of the water through the top of the cyclone; this is typically referred to as overflow. The coarser material exits the cyclone through the apex, or spigot, located at the bottom of the cyclone, at a relatively high solids content (typically 70% solids by weight). The overflow comes out at a low solids content (typically 15% solids by weight).

Figure I-6 Schematic of a Cyclone Demonstrating the Principle of Centrifugal Acceleration (Kujawa 2011)



Tailings Segregation - Sulphide Flotation

Flotation of sulphides may be used to remove most of the sulphide minerals from the tailings and concentrate them in a smaller, separate sulphide tailings stream. Typically, this may be achieved with the processing separation of “cleaner” and “rougher” tailings. This can allow separate deposition of the not potentially acid generating (NPAG) tailings and the potentially acid generating (PAG) tailings using appropriate technology for each. The high sulphide fraction could potentially be separately stored in underground openings as a cemented paste or dewatered tailings.

At some mines, the neutralization potential (NP) of the scavenger tailings is very low or ineffective, such that the tailings may still be considered acid generating (AG) or PAG, even at the relatively low sulphide concentrations. Under these circumstances, separate sulphide flotation circuits have been employed to enhance the final removal of sulphides, such that a NPAG tailings product is produced (typically less than 0.3% sulphide, but this depends upon the quantity and effectiveness of the NP).

Sulphide flotation is done through a process called froth flotation. The surface properties of minerals (composition and electrical charge) are used in combination with collectors(heterogeneous compounds containing a polar component and a non-polar component), for selective separation of minerals (sulphides in this case). The nonpolar hydrocarbon chain provides hydrophobicity to the target mineral (sulphide in this case) after adsorption of the polar portion of the collector on the surface.

The ore or tailings need to be fine enough that the minerals are exposed at the surface. The fine minerals are then combined with water into a slurry and the collector is added. The slurry (also called pulp) is put in a flotation cell where it is aerated to produce bubbles. The hydrophobic particles (target minerals) attach to the air bubbles that rise to the surface, to form a froth that can be collected separately from the other particles.

I-4 OTHER DEPOSITION TECHNOLOGIES

I-4.1 Sub-aqueous Tailings Deposition

Sub-aqueous deposition involves submerging tailings within a water body to prevent acid generation and, in some cases, limit metal leaching. Placing tailings underwater restricts exposure to oxygen, thereby inhibiting sulphide oxidation and acid generation in PAG tailings. It can also be done to prevent the tailings with high moisture contents from freezing.

Submerging tailings behind engineered dams is common for PAG tailings. These dams must be designed and constructed to provide physical and geochemical stability for closure. Sufficient precipitation and/or runoff must also be available to maintain a water cover to ensure that the tailings remain submerged.

Existing natural water bodies (e.g. lakes) can also be used for sub-aqueous tailings deposition. These options offer low construction, operating, and closure risks and costs. However, in Canada, this type of tailings deposition requires an amendment to Schedule 2 of the Metal Mining Effluent Regulation (MMER), which can be a lengthy and challenging process and, ultimately, may have extreme social and environmental consequences.

I-4.2 In-Pit Tailings Deposition

In-pit tailings deposition may be used when a mined-out pit becomes available during the operating life of the mine, or if a pit can be partitioned to separate the tailings from the active mining. Not all pits are suitable for the in-pit deposition of tailings. Success depends on many factors, including:

- if the pit is already flooded, management of the displaced water;
- availability of open pits in the mining sequence, as typically the open pit may not be available until mining is completed;
- geochemical properties of the tailings and pit walls;
- geotechnical properties of the tailings and pit walls;
- predicted pore water, pit water, and groundwater quality;
- hydrogeology of the open pit; and
- hydrology of the open pit.

An important consideration for in-pit deposition is the contact of the tailings with the pit walls and the potential for seepage pathways through faults or fracture zones in the walls. Hydrogeologic confinement of the tailings may be possible where the pit can act as a regional groundwater discharge zone or "sink." Where this is not possible, pervious surrounding drain systems have been used to isolate in-pit wastes from the regional groundwater flows.

Permanent submergence of PAG tailings in an open pit is an appealing option to mitigate ML/ARD. However, the potential for runoff to mobilize secondary reaction products such as acidity, sulphate and metals from the permanently exposed pit walls needs to be considered. Flooding of sulphide-bearing tailings at closure may also flush and mobilize metals from the tailings. Both these effects must be considered in assessing the groundwater and surface water impacts, and the potential need for water treatment systems. Regional groundwater flow movement also needs to be considered with respect to the fate and transport of tailings pore water.

Mine-related constraints must be taken into consideration: ensuring access to remaining mineralization below the pit; pit wall stability and related safety concerns; available access; and the proximity of underground workings to the open pit.

I-4.3 Tailings and Waste Rock Co-Deposition

Co-Deposition

Co-deposition of tailings and waste rock involves encapsulating tailings within waste rock dumps. The selection of the most appropriate co-deposition technique varies from site to site, and depends on factors such as the available land area and topography, the ratio of tailings to waste rock (strip ratio), waste rock type (fine or coarse sized), and tailings consistency (fine or coarse-grained, slurry or filtered). The tailings-waste rock repository may be simply capped with a cover for closure, or it may be submerged by flooding, either progressively during the mine operating life, or at closure.

Co-deposition of tailings and waste rock as the primary mine waste management strategy may offer attractive economic and environmental benefits for some mines. These benefits could include:

- reduced area of land disturbance by the waste rock dumps and tailings facilities;
- increased safety and reduction of the risks associated with tailings facilities by eliminating or reducing the size and height of the tailings facilities; and
- reduced potential for ML/ARD in waste rock dumps (if they are carefully designed).[1]

Co-deposition of tailings with waste rock can theoretically be accomplished by a variety of placement methods, including the following:

- co-mingling of tailings in the voids of the waste rock by mixing at active dump tip heads;
- deposition of tailings in small to large cells formed in the interior of waste rock dumps;

[1] High saturation of the waste rock voids with tailings will tend to reduce oxygen flow through the dump and reduce the overall hydraulic conductivity of the dump.

- deposition of tailings in thin layers within waste rock dumps;
- mixing of tailings with crushed rock to achieve a moist mixture that can be placed and compacted in the waste dumps;
- mixing of tailings with crushed rock to achieve a saturated, non-segregating mixture that can be stored in an un-compacted state in cells within the waste dumps; and
- co-placement of tailings and rock in an impoundment, and submerging both at closure.

There are a multitude of issues to be addressed for the implementation of co-deposition of tailings and waste rock. The most significant of these include the following:

- implementation issues with mechanically mixing tailings and waste rock to produce a consistent stream;
- operational issues, including scheduling of waste rock and tailings production, and the increased workforce and management requirements;
- the impact of the tailings on dump seepage patterns and water levels;
- impact of the tailings on effective waste rock strength and overall dump stability, as well as local stability of the tip heads;
- the potential for long-term migration of the tailings from the dump; and
- ML/ARD mitigation.

Effective co-deposition of thickened tailings and waste rock by co-mingling layers or cells in waste dumps requires mine strip ratios at least on the order of 6:1 by volume and, therefore, complete co-mixing would not be feasible at mines with low strip ratios. Co-deposition may also not be suitable for surface tailings deposition at underground mines where waste rock production is usually minimal and a large proportion of the rock is stored underground.

Mixing of thickened tailings with crushed rock to form non-segregating mixtures can allow full tailings storage at strip ratios of 3:1 to 4:1, but at a penalty of much higher costs for the rock crushing and materials handling (Klohn Crippen 2001).

Despite its potential advantages, the authors were not able to identify examples of practical application of co-deposition technologies.

Co-Placement

Co-placement of PAG rock with tailings is a technology that mitigates the ML/ARD potential of the mine rock and has been used at several mines (e.g. Mt. Milligan, British Columbia). The application of this technology should consider the physical setting (e.g. travel distances for haulage of rock) and the implications of a larger tailings facility or higher dams to store both the tailings and the PAG rock.

The use of PAG rock for construction of the tailings dam has been applied at some sites and involves placing the rock upstream of the low-permeability core zone of the dam. As it is permanently saturated in that location, it will not produce ML/ARD.

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APPENDIX II

Tailings Technologies Case Histories

Appendix II
Tailings Technologies Case Histories

This appendix contains brief case histories of mines that have applied different tailings technologies. The case histories demonstrate how tailings management technologies, facility configurations and concepts have been applied to achieve project objectives across a variety of climates, geographies, tailings types, project configurations and other conditions.

A summary of information collected from the Canadian inventory and public sources on the case histories is provided in Table II-1.

Table II-1 Case History Summary (Information collected from public sources)

Mine Site	Owner/Operator	Status	Operation Start	Operation End	Location	Mine Type	Primary Resources	Tailings Production (tpd)	Climate: Mean Annual Precipitation (mm)	Climate: Mean Annual Evaporation (mm)	Climate: Mean Annual Temperature (°C)	Tailings Processing: Tailings Stream	Tailings Processing: Solids Content (Design)	Tailings Processing: Solids Content (Achieved)	Tailings Processing: Processing & Equipment	Tailings Processing: Transport Equipment	Tailings Properties: Specific Gravity	Tailings Properties: Liquid Limit	Tailings Properties: Plastic Limit	Tailings Properties: Plasticity Index	Tailings Properties: D50 (mm)	Tailings Properties: D80 (mm)	Tailings Properties: Fines Content (<74 µm)	Tailings Properties: Clay Content (<2 µm)
Conventional Slurry																								
Aitik	Boliden	Operating	1968		Sweden - Lapland	Open Pit	Cu	98,630	575	350					Conventional slurry	Centrifugal pump								
Bingham Canyon	Kennecott Utah Copper	Operating	1906		United States - Utah	Open Pit	Cu	176,000	400	1268														
Copper Cliff	Vale Canada Limited	Operating			Canada - Ontario	Underground	Ni		899	570														
Elkview Operations	Teck Coal Limited	Operating			Canada - British Columbia	Open Pit	Coal			550														
Hidden Valley	Hidden Valley Joint Venture	Operating	2009		Papua New Guinea - Morobe	Open Pit	Au, Ag	11,500	2900	1100	17													
Mount Polley	Imperial Metals Corporation	Operating	1997		Canada - British Columbia	Open Pit	Cu, Au	20,000						35%	Conventional slurry	Gravity flow								
Red Chris	Imperial Metals Corporation	Operating	2015		Canada - British Columbia	Open Pit	Cu, Au	30,000	530	420			34%		Conventional slurry	Gravity flow								
Red Dog	Teck Alaska Inc.	Operating	1989		United States - Alaska	Open Pit	Zn, Pb																	
Snap Lake	De Beers SA (Anglo American plc)	Care & Maintenance	2007		Canada - Northwest Territories	Underground	Diamond							73%										
Snow Lake	HudBay Minerals Inc.	Operating	2001		Canada - Manitoba	Underground	Zn, Cu			500														
Sullivan	Teck Metals Ltd.	Closed		2001	Canada - British Columbia	Underground	Pb, Zn, Ag			550														
Conventional Slurry - Cyclone Sand Dam																								
Brenda Mines	Xstrata Copper	Closed	1969	1990	Canada - British Columbia	Open Pit	Cu, Mo	30,000	633	650					Conventional slurry		2.70				0.079	0.226	48%	
Copper Mountain	Copper Mountain Mining Corporation	Operating	1972		Canada - British Columbia	Open Pit	Cu	37,500	452	490		Tailings		32%	Conventional slurry		2.76							
Gibraltar	Taseko Mines Limited	Operating	1972		Canada - British Columbia	Open Pit	Cu, Mo	85,000	510	550				40%	Conventional slurry	Centrifugal pump					0.067	0.160	53%	
Highland Valley Copper	Teck Highland Valley Copper Partnership	Operating	1962		Canada - British Columbia	Open Pit	Cu, Mo	135,000	394		4				Conventional slurry	Centrifugal pump								
Huckleberry	Huckleberry Mines Ltd.	Operating	1997		Canada - British Columbia	Open Pit	Cu, Ag	20,000	1043	376	3			24%	Conventional slurry	Centrifugal pump								
Kemess South	AuRico Metals Inc.	Closed	1998	2011	Canada - British Columbia	Open Pit	Cu, Au	54,000	750	223	1				Conventional slurry	Centrifugal pump	2.72							
Thickened Tailings																								
Alcan Vaudreuil Alumina Refinery	Rio Tinto Alcan	Operating	1940		Canada - Quebec	Refinery	Al_2O_3	2,465	980	450	3	Red Mud		50%	Deep cone thickener	Positive displacement pump	3.37	50%	35%	15%	0.006	0.042	86%	30%
Aughinish Alumina	RUSAL	Operating	1983		Ireland - Munster	Refinery	Al_2O_3	3,288				Red Mud		58%	Vacuum filtration		3.30				0.004	0.021		35%
Canadian Malartic	Canadian Malartic Partnership	Operating	2011		Canada - Quebec	Open Pit	Au	55,000	914		1				65 m high-wall thickeners	Centrifugal pump								
Candelaria	Lundin Mining Corporation	Operating	1995		Chile - Atacama	Open Pit/Underground	Cu, Au, Ag	70,000	17					50%	2 - 122 m conventional thickener	Centrifugal pump								
Cardinal River	Teck Coal Limited	Operating			Canada - Alberta	Open Pit	Coal			550														
Cerro Verde	Freeport-McMoRan	Operating	1976		Peru - Arequipa	Open Pit	Cu	120,000	35	2100				58%	2 - 75 m conventional thickeners	Gravity flow						0.125	68%	
Chuquicamata	Codelco	Operating	1910		Chile - Antofagasta	Open Pit	Cu	182,000	5	3040				55%										
Collahuasi		Operating			Chile - Atacama	Open Pit	Cu	66,500						52%										
Duck Pond	Teck Resources Limited	Closed	2007	2015	Canada - Newfoundland and Labrador	Underground	Cu, Zn																	
Jackpine	Canadian Natural Resources Limited	Operating			Canada - Alberta	Open Pit	Oil Sands			588														
Kidd Creek	Glencore plc	Operating	1973		Canada - Ontario	Underground	Cu, Zn	8,000	765	420	1			63%	35 m Outokumpu SUPAFLO high compression thickener	Centrifugal pump	3.10				0.010	0.056	85%	10%
Meadowbank	Agnico Eagle Mines Limited	Operating	2010		Canada - Nuvavut	Open Pit	Au																	
Miduk	National Iranian Copper Industries Company	Operating	2005		Iran - Kerman	Open Pit	Cu	13,700	265	2000			63%	57%	4 - 16 m thickeners	Gravity flow		23%	16%	7%	0.022	0.095	72%	15%
Mont-Wright	ArcelorMittal Mining Canada G.P.	Operating	1976		Canada - Quebec	Open Pit	Fe			340														
Muskeg River	Canadian Natural Resources Limited	Operating			Canada - Alberta	Open Pit	Oil Sands			588														
Musselwhite	Goldcorp Inc.	Operating	1997		Canada - Ontario	Underground	Au	4,500	733	410				68%	16 m high compression thickener	Centrifugal pump	3.20						70%	
Oyu Tolgoi	Turquoise Hill Resources	Operating	2013		Mongolia - Ömnögovi	Open Pit	Cu, Au	100,000	57	2631	9		64%	59%	2 - 80 m thickeners	Centrifugal pump					0.050		55%	11%
Sar Cheshmeh	National Iranian Copper Industries Company	Operating	1974		Iran - Kerman	Open Pit	Cu	60,000	260	2800														
Selbaie	BHP	Closed	1981	2004	Canada - Quebec	Open Pit	Au, Cu, Zn, Ag	7,600		400					13.7 m high capacity thickener									
Snap Lake	De Beers SA (Anglo American plc)	Care & Maintenance	2007		Canada - Northwest Territories	Underground	Diamond	3,150	375	293	-8			73%	Deep cone thickener									
Sudbury Integrated Nickel Operations	Glencore Canada	Operating	1968		Canada - Ontario	Underground	Ni, Cu, Co, Pt	6,027		580														
Voisey's Bay	Vale Canada Limited	Operating			Canada - Newfoundland and Labrador	Open Pit	Ni, Cu, Co			320														
Paste Tailings																								
Bulyanhulu	Acacia Mining	Operating	2001		Tanzania - Shinyanga	Underground	Au	3,300	1200	1600	25		74%	73%	2 high rate thickeners, vacuum disc filters	Positive displacement piston pump	2.98	23%	20%	3%	0.025	0.097	74%	10%
Cobriza	Doe Run	Operating			Peru - Huancavelica	Underground	Cu	1,484	63			Cyclone Overflow		77%	14 m Dorr-Oliver EIMCO deep cone thickener	Positive displacement pump								
Myra Falls	Nyrstar	Care & Maintenance	1985		Canada - British Columbia	Underground	Zn, Pb, Cu	3,600	2509	548		Cyclone Overflow			High-rate thickener, Dorr-Oliver disc filter	Positive displacement pump					0.008	0.032	98%	20%
Neves Corvo	Somincor	Operating	1989		Portugal - Alentejo District	Underground	Cu, Zn	4,800	484	1313					Deep cone thickener		3.45				0.009	0.033	94%	13%
Filtered Tailings																								
Alamo Dorado	Pan American Silver Corporation	Operating	2007		Mexico - Sonora	Open Pit	Au, Ag	4,000	800	2065	26		82%		2 vacuum belt filters at 160 m2	Conveyor, truck placement								
Bellekeno	Alexco Resource Corporation	Care & Maintenance	2011		Canada - Yukon Territory	Underground	Ag	188	280	200		Low Pyrite Tailings			Filtered	Truck								
Catalina Huanca	Trafigura	Operating			Peru - Ayacucho		Zn, Ag, Pb	2,000							Filtered	Truck								
Cerro Lindo	Milpo	Operating	2007		Peru - Ica	Underground	Zn, Pb, Cu	6,480	200	1500	19			88%	30 m high compression thickener, Delkor vacuum belt filter	Truck	4.10	12%				0.207	57%	
Coal Mountain	Teck Coal Limited	Operating			Canada - British Columbia	Open Pit	Coal			550														
Eagle River	Wesdome	Operating	1995		Canada - Ontario	Underground	Au			520														
Efemçukuru	Eldorado Gold	Operating	2011		Turkey - Izmir	Underground	Au	700	740	1203	15				Vertical plate pressure filteration	Truck	2.90	24%	21%	3%		0.067		
El Indio		Closed		2002	Chile - Elqui	Open Pit/Underground	Cu, Au																	
El Penon	Yamama Gold	Operating	2000		Chile - Antofagasta	Underground	Au, Ag	4,200	50	3631				83%	Vacuum belt filtration	Truck	2.61						63%	
El Sauzal	Goldcorp Inc.	Closed	2004	2014	Mexico - Chihuahua	Open Pit	Au	5,770	800	2400	18		85%		Vacuum belt filtration	Conveyor, truck placement								
El Toqui	Nyrstar	Operating	1983		Chile - Aysén	Underground	Zn, Pb, Au	1,725	1480	500	7	Surface Filtered Tai		84%	14 m diameter deep cone thickener, 2 vacuum disc filters with 10 discs each (3200 mm diameter)									
Éléonore	Goldcorp Inc.	Operating	2015		Canada - Quebec	Underground	Au	4,000	720	250	1				Pressure filtration									
Escobal	Tahoe Resources	Operating	2013		Guatemala - Jalapa	Underground	Ag	1,528	1689	848		Flotation Tailings	87%	84%	Pressure filtration	Truck								
Fording River	Teck Coal Limited	Operating			Canada - British Columbia	Open Pit	Coal																	

Mine Site	Owner/Operator	Status	Operation Start	Operation End	Location	Mine Type	Primary Resources	Tailings Production (tpd)	Climate: Mean Annual Precipitation (mm)	Climate: Mean Annual Evaporation (mm)	Climate: Mean Annual Temperature (°C)	Tailings Processing: Tailings Stream	Tailings Processing: Solids Content (Design)	Tailings Processing: Solids Content (Achieved)	Tailings Processing: Processing & Equipment	Tailings Processing: Transport Equipment	Tailings Properties: Specific Gravity	Tailings Properties: Liquid Limit	Tailings Properties: Plastic Limit	Tailings Properties: Plasticity Index	Tailings Properties: D50 (mm)	Tailings Properties: D80 (mm)	Tailings Properties: Fines Content (<74 µm)	Tailings Properties: Clay Content (<2 µm)
Gold Road	Mojave Desert Minerals, LLC	Closed	1905	2015	United States - Arizona	Underground	Au	500	261	2560			86%	87%	Thickener, plate pressure filters	Grasshopper conveyors, spread with	2.63				0.018	0.060	87%	
Greens Creek	Hecla Mining Company	Operating	1989		United States - Alaska	Underground	Ag, Au, Zn, Pb	750	1450	371	5			88%	3 - 32 plate SALA pressure filters	Truck	3.50	19%	16%	3%	0.030	0.075	80%	3%
Karara	Karara Mining Ltd.	Operating	2013		Australia - Western Australia	Open Pit	Fe	35,000	310	3875	20	Fine Fraction	85%	87%	Pressure filtration	Stacking conveyor						0.035		
												Coarse Fraction	85%	87%	Dewatering screens	Stacking conveyor						1.500		
La Coipa	Kinross	Care & Maintenance	1990		Chile - Atacama	Open Pit	Au, Ag	18,000	9	3631				81%	2 thickeners, vacuum belt filtration	Stacking conveyor	2.77						54%	
Line Creek	Teck Coal Limited	Operating			Canada - British Columbia	Open Pit	Coal			550														
Mantos Blancos	AngloAmerican	Operating	1959		Chile - Antofagasta	Open Pit	Cu	12,000	50	3631		Cyclone Underflow		83%	Vacuum belt filters - transitioning to dewatering screens	Stacking conveyor	2.68						38%	
Marlin	Goldcorp Inc.	Operating	2005		Guatemala - San Marcos	Open Pit/Underground	Au	6,000	1136	1111	19			84%	Plate pressure filters with lime and cement addtion as needed	30 t articulated trucks								
Meliadine	Agnico Eagle Mines Limited	Construction			Canada - Nunavut	Open Pit/Underground	Au	5,000	412	150	-11		86%		3 recessed plate filter presses (2 in operation, 1 standby). Filtered tailings mixed with cement to create pase backfill as-needed. Remaining tailings placed in dry stack TSF. 2.5 Mt to be used as backfill, 9.5 Mt to be placed in TSF.	Truck transport <1 km, dozer, compac					0.020	0.066	83%	
Minto	Capstone Mining Corp.	Operating	2007		Canada - Yukon Territory	Open Pit/Underground	Cu	3,800	250	300	0	Low Pyrite		86%	13.5 m thickener, 5 Lasta 1500 mm by 1500 mm pressure filters									
Pogo	Sumitomo	Operating	2006		United States - Alaska	Underground	Au	1,360	356	140	-2		87%		Pressure filtration	Truck			20%		0.027	0.075	80%	7%
Pumpkin Hollow	Nevada Copper	Proposed			United States - Nevada	Open Pit/Underground	Cu, Au, Ag, Fe	55,872	123	1727	12		87%		Pressure filtration									
Raglan	Glencore Canada	Operating	1997		Canada - Quebec	Underground	Ni, Cu	3,520	520	100	-10			85%	Svedala pressure filtration	35 tonne trucks							70%	
Rosemont	HudBay Minerals Inc.	Proposed			United States - Arizona	Open Pit	Cu, Mo	75,000	436	1817			87%		Pressure filtration	Stacking conveyor	2.96	21%	20%	1%			73%	
San Dimas	Primero	Operating	1883		Mexico - Durango	Underground	Au, Ag	2,500	87	2400					Vacuum belt filter									
Skorpion Zinc	Vedanta Resources	Operating	2008		Namibia - Karas	Open Pit	Zn	5,040	20	3000			60%	60%	Vacuum belt filter	Stacking Conveyor	2.75	78%	70%	8%	0.017	0.099	75%	13%
Lake																								
Eskay Creek	Barrick Gold	Closed	1994	2006	Canada - British Columbia	Underground	Au	300	2100	350				88%	Thickener, Larox PF 60 horizontal plate pressure filter	Truck							78%	
Iron Ore Company of Canada	Iron Ore Company of Canada	Operating	1962		Canada - Newfoundland and Labrador	Open Pit	Fe			340														
River																								
Grasberg	Freeport-McMoRan	Operating	1972		Indonesia - Papua	Open Pit/Underground	Au, Cu	240,000	11000	1500														
Ok Tedi	Ok Tedi Mining Ltd.	Operating	1984		Papua New Guinea - Western Province		Cu, Au	55,000	12000	1750														
Porgera	Barrick (Niugini) Ltd.	Operating	1989		Papua New Guinea - Enga	Open Pit	Au	17,800	3700	1500														
Ocean																								
Batu Hijau	PT NMR Newmont Mining Company	Operating	2000		Indonesia - West Nusa Tenggara	Open Pit	Cu, Au	112,000	2700	1600														
Bougainville	Rio Tinto	Closed		1989	Papua New Guinea - Autonomous Regio	Open Pit	Cu	130,000	4400	1500														
Britannia Beach	Anaconda Copper Company	Closed	1904	1974	Canada - British Columbia	Underground	Cu, Zn, Au, Ag	6,400	2230	650	10				Conventional slurry	Gravity flow								
Island Copper	BHP Minerals Inc.	Closed	1971	1996	Canada - British Columbia	Open Pit	Cu, Au, Ag, Mo	50,000	1871	620				43%	2 - 114 m thickeners	Gravity flow								
Kitsault		Closed	1967	1982	Canada - British Columbia	Open Pit	Mo			520														
Lihir	Newcrest Mining	Operating	1997		Papua New Guinea - New Ireland	Open Pit	Au	11,800	3500	1750														
Misima		Closed	1989	2004	Papua New Guinea - Milne Bay	Open Pit	Au, Ag	15,000	3500	1625	25													
Ramu	MCC Ramu, MRDC	Operating	2012		Papua New Guinea - Madang	Open Pit	Ni, Co	6,000	2442	1750														
Simberi	St Barbara Limited	Operating	2008		Papua New Guinea - New Ireland	Open Pit	Au	9,000	3000	1750														
Tasu	Wesfrob Mines Limited	Closed	1967	1983	Canada - British Columbia	Open Pit/Underground	Fe, Cu	6,000	4064	550														

II-1 CYCLONED SAND DAMS

II-1.1 Highland Valley Copper – Highland TSF

Highland Valley Copper is an operating, 135 000 tpd open pit copper mine located 80 km southwest of Kamloops, British Columbia. Slurry tailings are currently deposited into the Highland Tailings Storage Facility, which is a conventional facility valley impoundment contained by the cycloned sand L-L Dam at the west side and the rockfill H-H Dam at the east side (KCB 2014). The impoundment is approximately 10 km long and 2 km wide and currently holds approximately 1.35 Bt of tailings, with a permitted capacity of 2.1 Bt. The tailings impoundment is designed to store the probable maximum flood (PMF) and currently has capacity to store over 2 times the PMF.

The H-H Dam is an 88 m high zoned earthfill dam constructed from borrowed materials and waste rock, while the L-L Dam is a 157 m high zoned earthfill dam constructed primarily from cycloned sand with a till core and gravel drainage blanket (KCB 2014). The L-L Dam also features a zone of compacted cycloned sand upstream of the till core. The current permitted height of the L-L Dam is 179 m. Both the L-L Dam and H-H Dam are raised annually using the centreline construction method. Seepage through both dams is collected at the base of the dams and pumped back to the tailings pond.

Figure II-1 L-L Dam

Source: KCB 2017

Site Conditions

Highland Valley Copper is located in a climate with a mean annual precipitation of approximately 390 mm and slightly higher annual evaporation. Temperatures range from a minimum mean daily temperature of -7°C in December and January to a maximum mean daily temperature of 14°C in July and August. The site is considered moderately seismic with a design earthquake of magnitude 0.32 g used for the L-L Dam (KCB 2014).

TSF Operations

Whole tailings from the mill are primarily discharged as a slurry from the H-H Dam, where they flow towards the tailings pond near L-L Dam forming a beach several kilometers wide. A smaller portion of the tailings are pumped to the L-L Dam, primarily for dam construction.

Cycloned sand for construction of L-L Dam is produced using dual-stage cycloning, with primary cyclones located in a cyclone house on the dam abutment and secondary cyclones located along the dam crest (Willms et al. 2011). Cycloned overflow (fine tailings) is discharged into the impoundment from the L-L Dam while cycloned underflow is used for dam construction. Cycloned underflow is hydraulically placed — by depositing it as a slurry into cells — and compacted to greater than 97% Standard Proctor Density by downwards draining of excess water and track-packing by dozers. Cycloned sand is placed in the downstream dam shell for six to ten months of the year. During the remainder of the year, tailings received at the L-L Dam are deposited in the impoundment and used for beach construction. Placement of cycloned sand is relatively insensitive to weather conditions and can be continued during periods of heavy rainfall.

Reasons for Technology Selection and Realized Benefits

The cycloned sand tailings dam for the Highland TSF provides Highland Valley Copper with an effective, relatively uncomplicated to construct, cost-effective, tailings management solution. Constructing the L-L Dam from cycloned sand (a) eliminates the need for filter zones between tailings, core and downstream cell; (b) reduces dependence on borrow areas for dam fill; (c) reduces the size of the impoundment by using a portion of tailings for dam construction; and (d) reduces the overall cost of dam construction.

The till core in L-L Dam serves to limit seepage through the cycloned sand dam from the reclaim pond, which is in close proximity to the dam.

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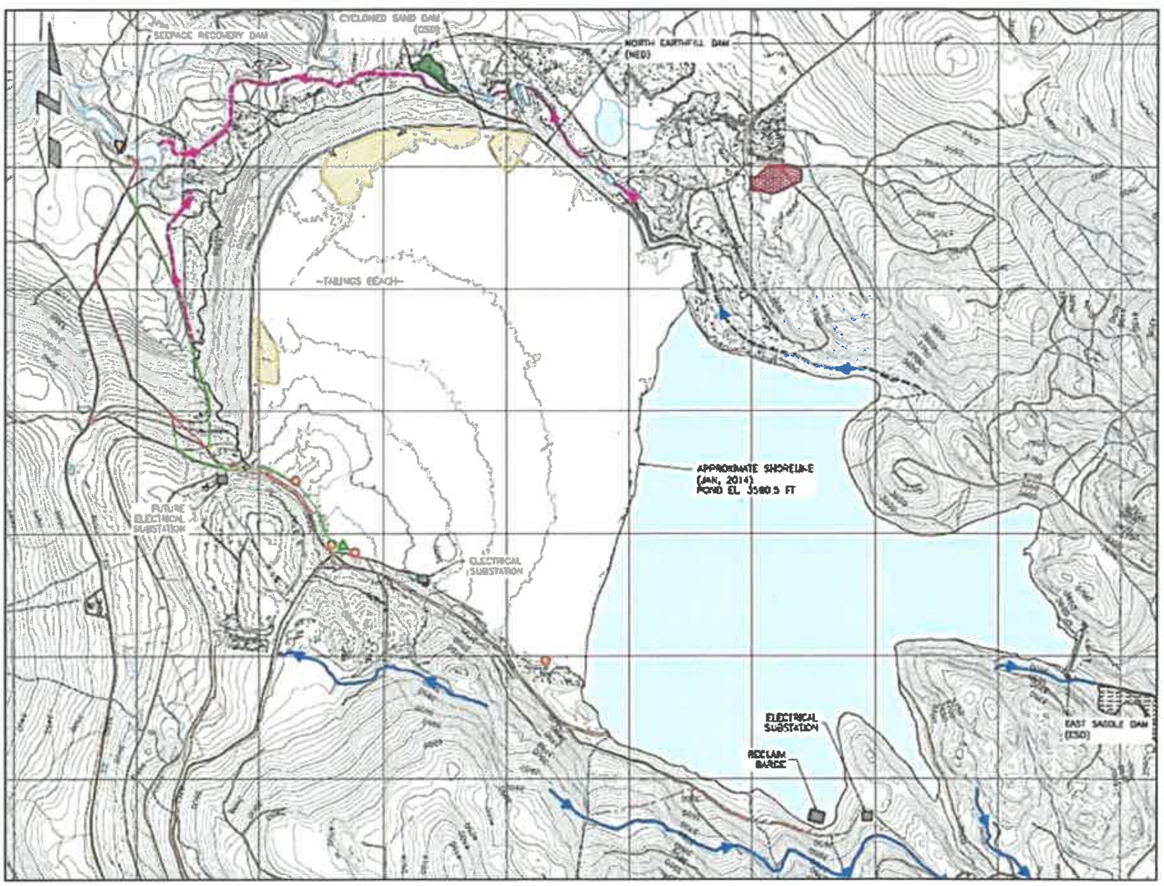
II-1.2 Gibraltar Mine

Gibraltar Mine is an operating, 86 500 tpd open pit copper mine located 44 km north of Williams Lake, British Columbia. The TSF is a conventional slurry tailings impoundment contained by the Main Dam on the northwest side and a relatively small earthfill dam (the East Saddle Dam) on the southeast. The Main Dam is composed primarily of a larger cycloned sand dam with a smaller, earthfill dam on the northeastern flank (the North Earthfill Dam; KCB 2014). Seepage collection ponds are located below the Main Dam and the East Saddle Dam. The Main Dam has a tailings beach approximately 760 m to 2440 m wide, while the East Saddle Dam functions as a water retaining dam on the east side of the facility. The facility is approximately 4.6 km long and 1.2 km to 2.4 km wide.

The Cycloned Sand Dam is the primary focus of this case history, and is currently 115 m high. It does not have a core but relies on a minimum 457 m-wide upstream beach for dam safety and stability. Finger drains are provided beneath the dam to maintain a low phreatic surface.

Figure II-2 Gibraltar Mine Tailings Storage Facility



Source: KCB 2014

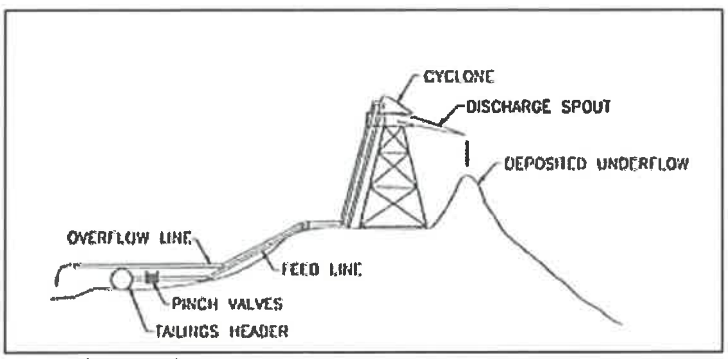
Site Conditions

The mean annual precipitation at Gibraltar is 521 mm, 35% of which typically falls as snow (KCB 2014). Temperatures range from an average monthly minimum of 0°C to an average monthly maximum of 9°C, with a mean annual temperature of approximately 4°C. A peak ground acceleration of 0.21g (design update currently in progress; KCB 2012) was adopted for seismic design, corresponding to a magnitude 6 earthquake occurring 20 km from the TSF.

TSF Operations

Tailings are deposited primarily from the south abutment of the Main Dam as cycloned underflow and overflow, and from around the perimeter of the Main Dam as both whole tailings and cycloned underflow and overflow (KCB 2014). Historically, cycloned sand for dam construction was produced using single-stage cyclones along the dam crest. Up until the closing of the mine in 1998, the underflow (coarse fraction) was deposited directly on the downstream face of the dam from the cyclones on the dam crest, while the overflow (fine fraction) was deposited in the tailings facility (Figure II-3). No mechanical compaction was applied to tailings on the downstream dam face (Plewes et al. 1997). Deposition of cycloned sand was generally done from March to October each year and continued during periods of heavy rainfall. Over the years, occasional regrading of the dam face has been required to maintain the design outer slope of 2.5H:1V as the coarse sand tends to stand up steeper than the design slope. Since the mine was re-opened in 2004, the cycloned sand dam has been raised mechanically.

Figure II-3 Typical On-Dam Cyclone Setup at Gibraltar Mine



Source: Plewes et al. 1997

Reasons for Technology Selection and Realized Benefits

The cycloned sand dam at Gibraltar Mine has provided a relatively simple, cost-effective tailings management solution. The coarse nature of the cycloned underflow sand relative to the cycloned overflow or whole tailings, combined with the wide, upstream beach and finger drains beneath the dam, promotes stability by maintaining a low water table — expected to further decrease when deposition ceases post-closure — within the dam and tailings during deposition.

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II-1.3 Kemess South Mine

The Kemess South Mine was an open pit gold-copper mine, located in the Omineca Mountain Range of North-Central British Columbia, approximately 300 km northwest of Mackenzie. The tailings were stored in a conventional facility. Operations ceased in early 2011, and the site is in care and maintenance phase. The tailings dam has a low permeability core that keeps the PAG tailings and waste rock, upstream of the dam, saturated. The dam is partially founded on weak, pre-sheared glaciolacustrine soils at residual strength, which necessitated the addition of a large, downstream buttress and shear key to provide the required long-term stability; this resulted in an overall downstream slope of 5H:1V.

From starter dam construction in 1996 until 2002, the downstream dam shell and buttress was constructed of NPAG waste rock hauled 7 km uphill from the open pit. Due to the high cost of hauling rock, further construction was completed with NPAG cycloned sand. The cycloned sand could only be produced from one of the ore types processed, and required an additional flotation circuit to remove sulphides from the coarse underflow.

The tailings dam design was developed in direct consultation with an independent geotechnical review panel, that provided third-party oversight and technical guidance, on an annual basis, throughout the entire design and construction of the tailings facility.

Figure II-4 Kemess Tailings Facility

Source: Vancouver Sun 2014

REFERENCES

Vancouver Sun. 2014. Geotechnical inspection pinpoint concerns at mine dams: documents. Accessed February 20, 2017. http://www.vancouversun.com/business/Geotechnical+inspections+pinpoint+concerns+mine+dams+documents/10461730/story.html?__lsa=8694-5d30

II-2 THICKENED AND HIGH-DENSITY THICKENED TAILINGS

II-2.1 Canadian Malartic Mine

Canadian Malartic Mine is a 55 000 tpd open pit gold mine located 20 km west of Val-d'Or, Quebec, adjacent to the town of Malartic. The Canadian Malartic tailings facility was developed over an historic tailings facility and uses thickened tailings deposition. The TSF and other mine components are shown in Figure II-5.

Figure II-5 Canadian Malartic TSF

Source: Doucet et al. 2015

Site Conditions

The mine area has relatively flat topography with some small hills and a relief of approximately 50 m across the property (Mine Canadian Malartic 2014). The mean annual precipitation is 914 mm, with snow falling from October to May; the mean annual temperature is 1°C.

TSF Operations

Some of the existing dikes were used as start-up confining structures. The current mining plan includes a tailings facility that will ultimately accommodate the storage of 190 Mt of tailings within a footprint of 600 ha; the final planned embankment height is approximately 47 m above ground surface. Ultimately, active deposition in the tailings facility will be organized into nine deposition cells that are confined by permeable perimeter berms, or internal roads.

According to the initial design, the thickened tailings were planned to be deposited at 68% solids content from central discharge points. During the first years of production, thickened tailings had different behavior and actual solids content closer to 55% solids. In 2016, the solids content is 60%; the mine plans to increase the solids content to 63% to 68% within the next 12 months. The observations and updated field parameters were used in the design update.

After thickening, tailings are pumped to a detoxification plant for cyanide destruction, which reduces the cyanide concentration to 20 ppm or less.

TSF Closure

For the tailings and waste rock berms comprising the TSF, the initial plan included a layer of organic soil and revegetation. Given some uncertainties regarding the long-term acid drainage potential, the current plan includes an additional, low permeability layer that will minimize water infiltration and oxygen diffusion in the tailings. However, no final decision has been made regarding the low permeability cover material and the source of this material.

Reasons for Technology Selection and Realized Benefits

The main goal was to have, for safety reasons, limited water storage on the site. Thickening tailings also reduces the need for containment structures, reduces the footprint of the tailings facility and improves water recovery (Mine Canadian Malartic 2014). Placing the NPAG tailings over an existing PAG tailings deposit effectively mitigated ARD from the previous impoundment.

REFERENCES

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II-2.2 Musselwhite Mine

Musselwhite Mine is a 4500 tpd (maximum milling/processing capacity) underground gold mine located in northwest Ontario, 475 km north of Thunder Bay, that has been operating since 1997. The site uses thickened tailings to increase the capacity of their existing tailings facility by upstream stacking (Figure II-6).

Site Conditions

The mine site is relatively flat with 45 m of relief due to glaciation features (AMEC 2006). The mean annual temperature is 0°C (AMEC 2006) with below zero temperatures typical from November to March (Jewell and Fourie 2015). Annual precipitation is 733 mm and annual evaporation is 410 mm. The area has a very low seismic hazard.

TSF Operations

The tailings at Musselwhite Mine are deposited in a ring dyke impoundment that is partially contained by natural topography (Jewell and Fourie 2015). The perimeter embankment dams are up to 15 m high. In 2010, the mine changed from conventional slurry deposition, to thickened tailings, for tailings management. The thickened tailings are stacked in lifts, from perimeter spigots, in the interior of the impoundment, using upstream raises to increase the capacity of the facility from its original design of 13.7 Mt to 32.0 Mt. The upstream raises are at slopes of 4H:1V, or flatter. A separation dyke was also constructed to divide the TSF into a tailings cell and water management pond.

The tailings have a fines content (percent passing the #200 sieve) of 70% and are considered PAG with approximately 1.5% sulphur (Jewell and Fourie 2015). Tailings are pumped as slurry to the Thickening Plant, which is located at the northwest corner of the Tailings Management Area (TMA) approximately 3 km from the Mill. The Thickening Plant dewaters slurry tailings from an overall solids content of 50% (by weight) to about 68%. The underflow density may be reduced for operational reasons, such as reducing buildup around the discharge pipe under freezing conditions. The plant has been able to effectively perform under different feed densities and loads. The tailings deposition has a convex beach slope profile, with slopes as high as 3 to 4% close to the spigots discharge points, decreasing to 2% towards the center of the TMA.

Excess water from the tailings facility is discharged seasonally through a segmented polishing pond, and finally through a wetland for final polishing and treatment prior to release to the environment (Jewell and Fourie 2015).

TSF Closure

The original, conventional TSF planned a shallow water cover for closure (Jewell and Fourie 2015); however, adoption of thickened tailings has resulted in changing to a dry-cover closure strategy. Progressive reclamation is currently being implemented and several closure test plots were constructed in 2016 to optimize the final dry cover design. These test cover plots vary in thickness from 0.5 m to 1 m sand cover, and are capped with 0.4 to 0.6 m topsoil. Various instruments were established on each plot to including moisture and suction stations, water samplers and vibrating wire piezometers. Test results will determine the most desirable cover design for closure.

Reasons for Technology Selection and Realized Benefits

In 2010, the conventional tailings deposition was modified to thickened tailings deposition. Thickened tailings were adopted to increase the capacity of the existing facility by stacking thickened tailings layers over their existing facility (Jewell and Fourie 2015). The new deposition strategy resulted in changing from wet cover to dry cover for final closure, which will also reduce the potential for seepage, post-closure. Adopting the thickened tailings was more desirable from a community perspective, as this strategy allowed the mine to maintain the same footprint, minimize long-term seepage impacts and align with future progressive reclamation plans. A number of operational approaches are being employed to minimize dust. The switch to thickened tailings at a pulp density over 68% promotes a non-segregating and heterogeneous tailings deposition due to better particle interlocking and increased suction. Thickened tailings were also selected due to the benefits of reduced operational expenditure (OPEX), capital expenditure (CAPEX) and operational risk compared to a comprehensive analysis of other tailings disposal methodologies.

Figure II-6 Aerial View of the Tailings Management Area at Musselwhite Mine

Source: Goldcorp 2017

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II-3 PASTE TAILINGS

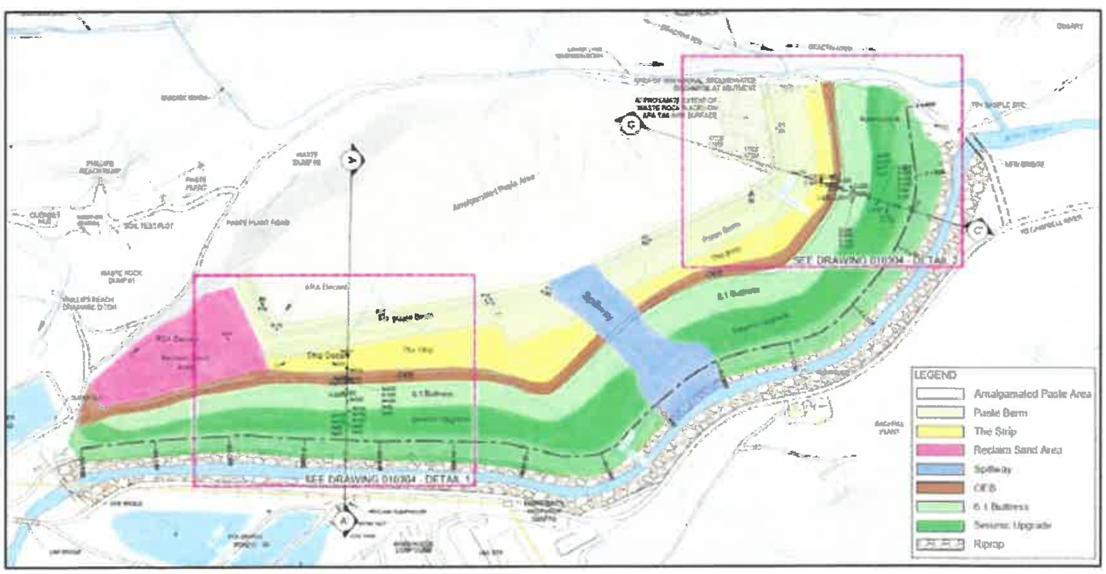
II-3.1 Myra Falls Mine

Myra Falls is a 1500 tpd copper, zinc, silver and gold mine located within Strathcona Provincial Park on Vancouver Island, British Columbia. Being located within a Provincial Park has led to requirements to reduce visual and environmental impacts, as well as the overall footprint of the mine.

Mining commenced in 1966 using both open pit and underground methods. Since 2001, mining has been only underground. Initial mining relied on subaqueous tailings disposal in Buttle Lake; however, in the 1980s the provincial government prohibited further tailings deposition in the lake, which led to the construction of a conventional slurry surface tailings facility, referred to as the Old TDF (AMEC 2014).

In the early 2000s, the Old TDF reached its design capacity using conventional slurried tailings. In order to allow further tailings placement in the Old TDF, paste tailings were adopted and deposited behind a rockfill berm on the top of the existing tailings. Paste tailings on the top of the Old Tailings Disposal Facility (TDF) allowed for a sloped top surface of the tailings, increasing storage capacity for the expansion. A plan view of the Old TDF is shown in Figure II-7, with a photo shown in Figure II-8.

Figure II-7 Old TDF – Plan View



Source: AMEC 2014 – Extracted from Drawing No. 010303

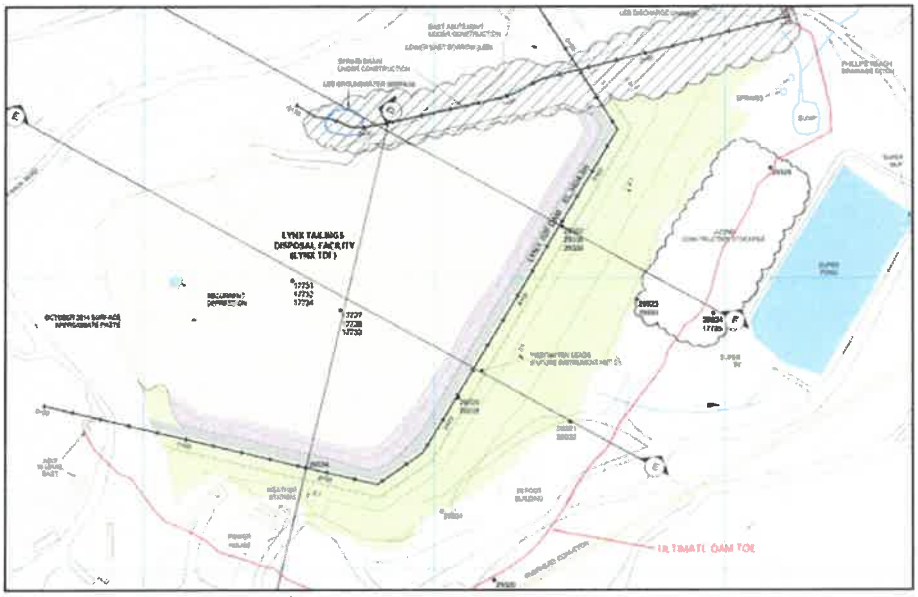
Figure II-8 Old TDF Paste Area

Source: AMEC 2014

After the paste tailings expansion of the Old TDF reached its capacity, paste tailings were deposited in an old, open pit, referred to as the Lynx TDF. A primary concern identified with depositing tailings in the existing open pit was that the tailings could flow into the underlying mine workings (through various tunnels and shafts) beneath the open pit following a seismic event (AMEC 2014). Although these workings were inactive, there was a concern that sudden tailings inflow could displace water into active workings. To mitigate this hazard, a cemented paste plug was installed in the pit bottom and the paste deposited in the pit was initially augmented with cement to increase its structural integrity.

As the Lynx TDF was filled above the Lynx Pit rim, a centreline rockfill tailings dam was constructed to contain the paste tailings (AMEC 2014). A plan view of the Lynx TDF is shown in Figure II-9 and a photo is shown in Figure II-10.

Figure II-9 Lynx TDF – Plan View



Source: AMEC 2014 – Extracted from Drawing No. 010307

Figure II-10 Lynx TDF Paste Area

Source: AMEC 2015

Site Conditions

Myra Falls is located in the Vancouver Island mountain ranges in the steep-sided, hanging valley of Myra Creek. It is a high rainfall area with mean annual precipitation and evaporation of 2509 mm and 584 mm, respectively. Mean daily temperatures fall below 0°C between December and February and rise over 20°C in July (Haile and Kerr 1989). The mine is located in a relatively active seismic zone, and liquefaction concerns have driven the design of many of the TSF components.

TSF Operations

The whole tailings from the mill are cycloned to separate the coarse and fine fractions. The majority of the cycloned underflow (coarse fraction) is mixed with cement and used for underground backfill, with excess underflow stockpiled for construction purposes (AMEC 2014). The cycloned overflow (fine fraction) is dewatered using a thickener, followed by vacuum disk filtration, to create paste tailings, which are then pumped to the Lynx TDF. When the filtration system is not operating, thickened tailings slurry are pumped directly to the Lynx TDF.

Paste tailings on the Old TDF were deposited from the hillside and allowed to flow towards the outer berm, forming a sloped surface. Paste tailings deposition in the Old TDF ceased in 2007 (Chalmers et al. 2008). Ongoing erosion of the paste slopes of the old TDF is resulting in deposition of the tailings paste against the outer embankment, as well as in the surface water treatment ponds (AMEC 2014). The tailings deposited against the outer embankment are gradually reducing the flood storage capacity of the rockfill berm containing the paste (AMEC 2014).

Reasons for Technology Selection and Realized Benefits

Paste tailings allowed for increasing the capacity of the existing Old TDF — without further raising the original embankment dam — by enabling deposition of tailings at a significant slope on the top surface. This has also led to ongoing erosion of the exposed tailings, which may require remediation in the future.

Paste tailings at the Lynx TDF allowed for tailings deposition in the old pit while underground mining occurred in nearby underground workings. Conventional slurried tailings may have been susceptible to rapid inflows into underground workings beneath the pit, which could have displaced water in active underground workings via existing fractures in the rock.

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II-3.2 Neves Corvo

Neves Corvo consists of an underground mine and an on-site processing facility, located 100 km north of Faro, Portugal. The copper plant has a processing capacity of 2.5 mtpa (million tonnes per annum) and the zinc plant has a capacity of 1.2 mtpa. Tailings from both plants were deposited sub-aqueously in a conventional TSF from 1988 to 2010. However, in 2010, thickened tailings deposition was adopted to increase the capacity of the existing facility without raising the perimeter embankments.

Site Conditions

Neves Corvo has a semi-arid climate with an annual precipitation of 484 mm and annual evaporation of 1313 mm (Lopes et al. 2013). The site is relatively flat with small hills and a total relief of less than 100 m.

TSF Operations

Tailings are thickened in a pair of deep cone thickeners to yield stresses typically exceeding 100 Pa in the underflow (Lopes et al. 2013). The thickeners are able to manage variable tailings feed rates and properties resulting from the periodic operation of a paste backfill plant that uses process plant tailings. The processing plant uses cyclones to separate a variable fraction of the total tailings from the tailings stream when the backfill plant is being used.

Currently the tailings are placed in deposition areas on the surface of the existing TSF that are delimited by peripheral waste rock berms (Lopes et al. 2015). The deposition areas are filled sequentially allowing a vertical expansion of the deposited tailings to achieve an overall 4% slope. When the planned final tailings level is reached, the deposition areas are reclaimed by placing a cover layer of waste rock. The current layout was selected in the face of increased tailings production, and represents a substantial change to the initial layout, which was based on 15 cells delimited by internal waste rock berms. Initial drying of the thickened tailings surface was delayed because the tailings were being deposited into ponded water on the existing unconsolidated tailings. However, after the depth of the thickened tailings increased to several meters, the rate of drying improved.

The tailings are PAG with approximately 50 wt% pyrite (Verburg 2015). The environmental stability of the tailings was investigated through laboratory bench scale tests, field cell tests and a paste pilot program before operation began in 2010 (Verburg 2016). These tests allowed placement protocols, cover type and geochemical predictions to be made prior to the beginning of operations, which are confirmed through water quality and paste pH testing during operations (Verburg 2016).

Reasons for Technology Selection and Realized Benefits

Thickened tailings were adopted to allow for expansion of the existing TSF without raising the perimeter embankments, and on the same footprint, by depositing the tailings in cells on the surface of the existing tailings facility (Lopes el al. 2013). The use of thickened tailings also reduces pyrite oxidation and seepage through the tailings, as well as allowing progressive and lower-cost mine closure options (Wardell Armstrong 2013).

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II-3.3 Snap Lake

Snap Lake is an underground diamond mine located 220 km northeast of Yellowknife, Northwest Territories. Tailings are stored in a high-density thickened/paste tailings facility. Following the discovery of kimberlite in the area in 1997, the mine received permits to operate and construct in May 2004 (Nuna 2016). The mine began operating in 2007, however, in December 2015 it was taken out of operation and put into care and maintenance. Snap Lake Mine is shown in Figure II-11. Tailings (processed kimberlite) are stored in North Pile Facility, shown in Figure II-11. Coarse processed kimberlite (CPK) is trucked to the North Pile, while fine processed kimberlite (FPK) is slurried for hydraulic deposition.

Figure II-11 Snap Lake Project Site

Source: De Beers 2016

Site Conditions

The Snap Lake project site experiences short, cool summers with long, cold winters. The average annual temperature is -4 °C. The site is just north of the boundary between discontinuous and continuous permafrost. Precipitation at the site is approximately 289 mm annually (De Beers 2013). The topography of the open tundra is gently sloping with a total change in elevation across the site of

37 m. A talik (unfrozen zone with discontinuous permafrost) exists beneath Snap Lake (De Beers 2003).

North Pile Facility Operations

The original processed kimberlite management plan was to dewater FPK using a deep cone thickener and transport the combined CPK and FPK paste slurry via pipelines to the North Pile Tailings Facility and Conveyor Decline Portal. The plan was to place over 50% of the paste underground, with the remainder going into the upstream-constructed North Pile Facility. When production began in 2007 (De Beers 2014), difficulties achieving the desired paste characteristics were encountered and small amounts of paste were placed underground up until 2015, when the mine went into care and maintenance. Similarly, in spite of sustained efforts, a stackable, non-segregating paste was never achieved for the North Pile Facility. In 2013, the design of the North Pile Facility was altered from an upstream to a centreline-raise design to accommodate storage of thickened FPK slurry (De Beers 2014), with the trucked CPK used for dam wall construction.

The following points highlight the technical challenges in creating sustainable paste tailings at the Snap Lake Mine as outlined by De Beers (2014):

- Variability of ore type, hence gradation, physical properties, and fluid characteristics;
- The tendency for kimberlite particles to break down in a pipe and flowing stream
- The limitations of laboratory testing in predicting slurry characteristics, particularly rheology (viscosity and solids content);
- The paste product exhibited hydraulic segregation, contrary to the design concept;
- Yield stresses lower than anticipated in design, compounded by the shear thinning rheology of the product;
- The difficulty of preparing a fluid of suitable water content for delivery to the deep cone thickeners; and
- The original failure, subsequently rectified after much effort, of the deep cone thickeners to perform adequately.

North Pile Facility Closure

The North Pile Facility is currently under extended care and maintenance. Surveillance, monitoring and maintenance continue at the facility. This includes annual geotechnical and geochemical inspections and monitoring of piezometers and thermistors (De Beers 2016). The water collection sumps and ditches around the facility, as well as the capability to control dust, are being maintained.

Permanent closure and reclamation plans of the North Pile Facility include regrading of the pile slopes and placement of a non-acid generating cover material (De Beers 2003).

Reasons for Technology Selection and Realized Benefits

The paste concept offered a number of benefits, such as efficiency of process water reclaim, ease of water management, no reclaim water pond on the North Pile (Golder), a stackable and workable product to form the containment structures via upstream raise geometry, a reduced footprint, more rapid freezing owing to reduced porewater content, and facilitation of progressive reclamation. Filtered tailings were not viable due to the clay content within the FPK.

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II-4 FILTERED TAILINGS

II-4.1 Greens Creek Mine

Greens Creek is an operating 2200 tpd underground polymetallic silver, gold, zinc and lead mine on Admiralty Island in Alaska, approximately 30 km southwest of Juneau. About 1,600 tons to 1,800 tons of tailings are produced daily and stored in a filtered facility. Since the start of operations in 1989, tailings have been deposited both as underground backfill and in an above-ground filtered tailings facility. Figure II-12 shows the Greens Creek tailings facility and one of the water treatment ponds.

Figure II-12 Greens Creek Filtered Tailing Pile

Source: Louisberger 2015

The Greens Creek tailings contain pyrite and are considered acid generating with a long lag time (Condon and Lear 2006).

Site Conditions

Greens Creek is located in a high rainfall, coastal environment. Mean annual precipitation is approximately 1450 mm and greatly exceeds annual evaporation. Periods of heavy rainfall lasting several days are common (Condon and Lear 2006). Mean annual temperature is approximately 6°C.

The site has high seismicity; the maximum design earthquake ground acceleration is 0.34g.

The mine is located within the Tongass National Forest and partially within the Admiralty Island National Monument. The island has some of the densest grizzly bear populations in the world and because of this, the mine operation is closely scrutinized to ensure environmental compliance.

TSF Operations

The Greens Creek tailings have a specific gravity of 3.5 and a P80 of approximately 75 µm. The tailings are approximately 34 wt% pyrite (Condon 2012). The monthly composite acid base accounting net neutralization potential has ranged between -500 to 25 tons $CaCO_3$ from 2001 to 2011.

Tailings from the ore processing facility are thickened by a rake drive thickener to 60% solids, then filtered to approximately 88% solids using pressure filtration. Tailings are then either combined with cement and used for underground backfill, or loaded into covered trucks and transported 13 km from the mill to the surface tailings facility. Approximately 50% of tailings are disposed of underground, with the remainder being disposed of on the surface. Tailings placed in the surface tailings facility are spread using dozers and compacted using vibratory drum rollers to achieve a target of 90% of Standard Proctor Density (Condon and Lear 2006). The tailings pile is approximately 40 m high with outer slopes on the order of 3H:1V. Compaction of the filtered tailings also restricts oxidation and seepage through the fine grained tailings.

Placement in the outer, structural portions of the embankment is done during periods of dry weather when adequate compaction is more readily achieved (Condon and Lear 2006). Central areas of the pile are used for placement during poor weather, when rain or snow inhibits the ability to maintain the required moisture content in the tailings for adequate compaction. During periods of wet weather, the tailings surface is often not trafficable by the rubber-tired haul equipment, and roads on the pile must be constructed using waste rock to allow access to the pile. Furthermore, due to the small tonnage of the mine, temporary covered tailings storage is provided at the ore processing facility for a few days of tailings production.

Surface runoff and seepage from the pile is collected in sediment ponds using a network of ditches, underdrains and sumps. Sediment collected in ponds and collection ditches is combined with new tailings and placed during dry periods. Water is treated before discharge in a water treatment plant at the tailings facility.

TSF Closure

Closure for the Greens Creek filtered tailings pile will involve placing a 2 m composite soil cover over the tailings (Condon and Lear 2006). The layer is designed to limit oxygen and water ingress into the tailings, and allow water to be shed from the pile. The cover will provide a growth medium for vegetation, including trees. The final outer design slope for the pile is 3H:1V. Water treatment is planned for as long as required to meet water quality requirements for discharge.

Reasons for Technology Selection and Realized Benefits

Primary reasons for adopting filtered tailings for the Greens Creek Project included minimizing the overall footprint and for site-specific geotechnical considerations. Reducing the overall footprint also allows for a significant reduction in the amount of water that must be treated.

Because there is no pond on the tailings surface, there is little potential for tailings to be mobilized and transported significant distances if the outer slopes of the pile were to fail during a seismic event.

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II-4.2 Raglan Mine

Raglan mine is an operating 4000 tpd nickel-copper mine located in the Nunavik region of Northern Quebec. The mine has seven decommissioned open pits and is currently extracting from four underground mines. Tailings are stored in a filtered tailings facility.

Site Conditions

The mine is located north of the arctic tree line in the continuous permafrost region characterized by a landscape of mounds of broken rock and shallow valleys with modest slopes (Holubec 2004). Mean annual air temperature is estimated to be -10.4° C and mean annual precipitation is 520 mm of which 50% is snow (Erazola 2013). Permafrost extends to a depth of 586 m below the ground surface and the active layer is about 1 m thick (Garneau 2012). The site is inland and at a relatively high elevation of 600 m which results in a colder climate than nearby coastal communities (Holubec 2004).

Tailings Properties

Tailings processing includes flotation and thickening before being pressure filtered to produce a filter cake with a moisture content between 12 to 15% W_w/W_t (Garneau 2012). The tailings contain up to 6% to 8% sulphides, mostly as pyrrhotite (Garneau 2012) and generate acidic runoff enriched in metals when exposed to air and moisture above freezing temperature. The net neutralization potential of the tailings is 118 kg $CaCO_3$ (Straub 2012). With an annual throughput of 1.32 Mt being processed by the concentrator, 1.1 Mt of tailings are generated (Garneau 2012).

Operations

Tailings disposal started in 1997. The dewatered filter cakes are trucked to a disposal site where they are dumped, spread, compacted, and formed into a mound (Erazola 2013). The plasticity of the tailings material allows it to keep its shape. The tailings stack is approximately 2 km from the process plant and is situated on a small plateau to minimize the amount of surface water flowing towards the material (

Figure II-13). Overburden at the stack site consists of 1 m thick layers of either ablation or lodgement till. Bedrock consists of volcanics and mafic to ultramafic intrusives (Holubec 2004).

Roads constructed of crushed rock are required in areas for trafficability (typically during wet, warm periods). There is also a temporary, emergency tailings storage pad (for 1 to 2 days of storage) for extreme winter/blizzard conditions.

A perimeter ditch collects runoff water and directs it to a collection pond from where it is pumped to a water treatment plant at the Katinnq facility (Holubec 2004).

To confirm and optimize the cover design, a test pad measuring 40 m by 40 m was constructed on a completed corner of the stack in November 2001. The test pad shows that the surface starts to thaw in early June and the thaw zone progresses deeper, reaching its maximum depth of 1.9 m, in September. Four additional test pads have been added as of 2011 in order to experiment technologies that are less affected by climatic changes.

Figure II-13 Tailings Stack for Raglan Mine

Source: Levac 2016

Closure

Encapsulation of tailings in permafrost was selected as the best closure option since the tailings are reactive and a water cover would be difficult to maintain in this dry region (Holubec 2004).

The effect of climate change was modeled over a period of 100 years; prediction beyond this length of time was deemed too uncertain (Erazola 2013). Prediction modelling for the Nunavik area shows that the ground temperature may increase by 3°C to 4°C by 2050 (Sushama et al. 2006; Garneau 2012). Within this context of possible thawing of the tailings material, studies were conducted to evaluate the capacity of the cover to prevent oxidation and prevent acid mine drainage in the long-term (Garneau 2012).

Analyses of available temperature data from various adjacent stations resulted in a mean annual air temperature (MAAT) being estimated at -8.8°C (Nixon 2000; Holubec 2004; Table 1), a thawing index of 707 degree-days (Holubec 2004) and the probability of an extreme warm year occurrence being one in 100 years with a thawing index of 976 degree-days (Holubec 2004). However, there were difficulties in selecting design air temperatures and thawing indices due to significant fluctuations of values over the available 20 years of records from the various sources (Holubec 2004).

The closure plan was to cover the tailings surface with two layers of granular material for a total thickness of 2.4 m to 1.2 m of 0 to 20 mm of crushed rock overlain by 1.2 m of non-reactive mine rock-fill for erosion protection and insulation. Raglan mine has decided to conduct a feasibility study with a geomembrane, which is less affected by the climatic changes.

The final tailings stack will cover 760,000 m^2 and have a maximum height of 30 m. The side slopes will be 5H:1V to protect the cover from erosion. The top of the stack will have about a 3% slope to allow runoff (Holubec 2004) and a 0.4 m layer of granular cover is being placed as a dust control measure.

Reasons for Technology Selection and Realized Benefits

The reasons for selecting filtered tailings were economic and waste water management-related. Borrow material for constructing starter facilities for a conventional tailings impoundment were scarce. Also, waste water management during winter in the North is a challenge. Even if the cost for filtering and stacking the tailings was found to be higher than conventional tailings, the fact that there is almost no waste water to manage minimizes water treatment costs and the risk of a spill. Raglan is located in an area that has a limited water source (especially during the winter), which prompted the company to initiate the zero process water discharge process in 2002. Further more, filtering the tailings had the added benefit of reducing process water needs.

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II-4.3 Minto Mine

The Minto Mine is a 4200 tpd open pit and underground copper, gold and silver mine located approximately 240 km northwest of Whitehorse, Yukon. Tailings were deposited into a filtered facility until 2012. Conventional in-pit storage facilities were used after 2012. A temporary closure was planned for 2017 due to market conditions, but has been postponed until at least late 2017. The site contains two in-pit tailings storage facilities and a dry stack tailings storage facility (DSTSF), shown in Figure II-14. Between 2007 and 2012 tailings were filtered and stacked in the DSTSF (EBA 2011) which is located in the upper basin of Minto Creek.

Figure II-14 Minto Mine Project Site

Source: CBC 2016

Site Conditions

The mine is located in a subarctic continental climate in discontinuous permafrost. Mean annual precipitation is 340 mm (EBA 2011) while mean annual temperature is -1.8°C (Capstone 2016). There is no exposed bedrock in the area of the DSTSF and the depth to bedrock in the area ranges 5 m to 50 m (Capstone 2016).

Tailing Properties

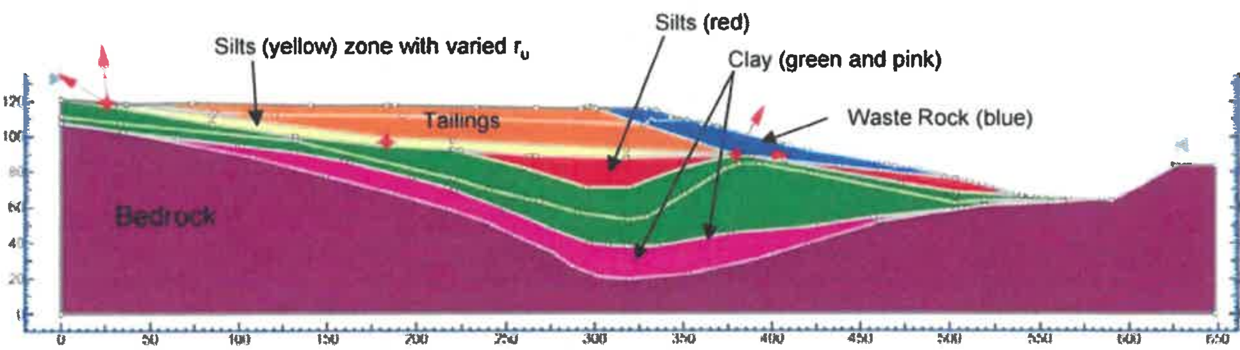
Tailings typically comprise of 59% sand, 35% silt and 6% clay, and have an average specific gravity of 2.72 (Capstone 2016). Prior to November 2012, tailings were filtered to 83% solids content by five Lorax filter presses before being transported by truck and placed in the DSTSF (EBA 2011, Capstone 2014). The in-situ tailings density in the DSTSF ranges from 1.8 to 2.2 tonnes/m^3 (Capstone 2016).

Operations

A pipeline routes flotation tailings from the mill to the tailings building where they are processed in a thickener. When filtered tailings were still being produced, the underflow from the thickener was put through a filter press to remove additional water. The filtered tailings were mechanically spread and compacted in controlled lifts on the DSTSF.

The surface area of the DSTSF is 0.4 km^2 (EBA 2011). The side slopes are 2:1 with an overall 4:1 non-acid generating waste rock cover (Capstone 2016), as shown in Figure II-15. The final maximum tailings thickness achieved at completion of the DSTSF was 25 m (Capstone 2016).

Figure II-15 DSTSF Cross Section



Source: SRK 2015

A diversion upstream of the facility diverts runoff around the facility. The surface of the DSTSF is graded to direct runoff to contact water conveyance channels, where it is collected in sumps and pumped to the Main Pit (Capstone 2016).

The facility is designed with a 120 m wide by 1.5 m-thick drainage blanket (waste rock overlain by a filter layer) at the starter toe bench (EBA 2007), with four finger drains to intercept seepage beneath the facility. Low amounts of seepage have been observed through operations and monitoring of the TSF that mix with seepage from other sources before collecting in the operational sump. The low seepage rates from the DSTSF have been attributed to the low permeability of the tailings and the presence of partially frozen tailings (Capstone 2016).

Movement of the DSTSF was identified beginning in 2009, with the movement occurring at depth within the ice-rich, warm, permafrost clay layer and along a relatively well-defined shear zone, above the bedrock contact (Capstone 2016). A buttress was constructed in two stages to arrest the DSTSF movement. Monitoring of the DSTSF has shown rates of movement slowing down since the construction of the buttress with monitoring to continue through closure (Capstone 2016).

Closure

A 1 m interim overburden cover was placed over the DSTSF in 2014. This cover will be modified — in order to meet closure requirements — with the appropriate soil type to achieve a vegetated cover and minimize infiltration (Capstone 2016).

Reasons for Technology Selection and Realized Benefits

Tailings were placed in the DSTSF starting in 2007 following a review of alternatives with stakeholders. Use of this methodology was determined to be the best fit considering a number of factors, including operation risk, long term sustainability, and cost. However, the DSTF was designed to hold waste only from the main pit deposit. An expansion was planned to deposit tailings slurry in the mined-out open pits after deposition in the dry stack facility ended in 2012 (Capstone 2011).

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II-4.4 Marlin Mine

Marlin Mine is a closed 6000 tpd (maximum milling/processing capacity) open pit and underground gold and silver mine located in the western highlands of Guatemala, in the municipality of San Miguel Ixtahuacán, 25 km west-southwest of the town of Huehuetenango, approximately 300 km northwest of Guatemala City. It is in an area of moderate to steep terrain with elevations ranging from 1,800 to 2,300 metres above sea level.

Marlin Mine commenced production in late 2005, operating as both an open pit and underground mine. Open pit operations ceased in the second quarter of 2011 as the final, higher-grade portion of the open pit was mined. During the open pit mining phase, slurry tailings were deposited in a surface tailings impoundment. Since early 2012, filtered tailings were used to backfill the open pit as part of the closure plan. Marlin Mine entered the closure phase in 2017, and by that time approximately 3,860,000 tons of filtered tailings have been placed in the open pit backfill.

Figure II-16 Marlin Mine Backfilled Open Pit

Source: Goldcorp 2015 (Video still)

Site Conditions

Marlin Mine has a warm, humid climate with average monthly temperatures ranging from 15.9°C to 20.2°C (Everlife, S. A. 2012). There are distinct wet and dry seasons, and mean annual precipitation is approximately 1136 mm, which is similar to the estimated annual evapotranspiration of 1111 mm.

TSF Operations

Tailings were thickened using deep cone thickeners, after which they were dewatered, using pressure filters, to approximately 19% moisture content (W_w/W_s). Lime and cement were added to the tailings, when required, to reduce the moisture content, increase structural strength, and improve trafficability of the backfill especially during rainy seasons. The addition of lime and cement also improved the geochemical properties of the tailings by providing neutralization potential to reduce acid generation from the tailings and pit walls.

Tailings from the filter plant were conveyed to a covered shed, from there they were loaded and transported to the open pit using articulated dump trucks, where they were quickly spread and compacted using dozers and vibratory drum rollers. Rapidly compacting allowed surface water to run off the tailings towards a sump where it was pumped from the pit. The surface of the filtered tailings dries rapidly after rainfall events due to the high evaporation. The covered shed also provided approximately two days of tailings storage during periods of heavy rainfall when weather conditions were too wet for placement.

TSF Closure

The closure plan for the filtered tailings backfill is to restore the topography of the pit to its pre-mining state and revegetate the surface (Everlife S. A. 2012). The planned final closure slope of the tailings is 2.5H:1V.

Figure II-17 Marlin Mine TSF Closure

Source: Goldcorp June 2017

Reasons for Technology Selection and Realized Benefits

Placing tailings in the pit eliminated the need for an additional separate TSF and provided long term stabilization of the pit walls (Everlife, S. A. 2012). Using filtered tailings to backfill the pit allowed for restoring the original topography and providing structural fill in the pit, which was above active underground works. It also limits long term groundwater contamination by allowing surface water to run off, reducing infiltration into the pit.

REFERENCES

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II-4.5 Escobal Mine

Escobal is a 3500 tpd underground silver mine in Jalapa Department, Guatemala. Since the start of operations in 2013, tailings have been placed in a filtered tailings facility. The information included in this case study is part of the public domain.

Site Conditions

The climate at Escobal has distinct wet (May to November) and dry (November to May) seasons, with a total annual precipitation of 1689 mm (M3 2014). There is little variation in temperature year-round, with monthly average highs ranging from 30°C to 33°C, and monthly average lows ranging from 14°C to 19°C.

TSF Operations

Tailings are thickened to approximately 60% solids content before being dewatered with pressure filters to approximately 15% water content (W_w/W_t) (M3 2014). After filtration, approximately 50% of tailings are conveyed to a paste plant and used for underground backfill, while the remainder is placed in the surface filtered tailings facility.

Tailings from the filter plant are conveyed to a stockpile at the base of the filtered tailings facility and temporarily stacked using a radial stacker (Figure II-18). They are then loaded onto trucks, dumped, spread and compacted in thin lifts. Mine rock is also used as structural fill within the tailings facility. Further drying of tailings is promoted in the warm climate by disking the tailings surface using farming equipment (visible in Figure II-19). Figure II-19 shows construction activities at Escobal.

Figure II-18 Escobal Filtered Tailings Stockpile

Source: M3 2014 – Figure 17-11

Figure II-19 Filtered TSF at Escobal

Source: M3 2014 – Figure 18-5

Reasons for Technology Selection and Realized Benefits

The primary reason for selecting filtered tailings at Escobal was to create a facility that upon closure is a stable landform (M3 2014). It has also resulted in a reduced footprint compared to a conventional TSF. Progressive reclamation will be practised throughout the facility life. At closure, the facility will be suitable for revegetation and land cover similar to the surrounding terrain.

REFERENCES

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II-4.6 Pogo Mine

Pogo Mine is a 1400 tpd underground gold mine in central Alaska that has been operating since 2006. Pogo dewaters its tailings and places a portion underground, as backfill, and a portion on the surface in a filtered tailings facility. The filtered tailings facility is located in the upper part of a valley and has a water storage pond below it, which collects seepage and surface runoff. The information included in this case study is part of the public domain.

Site Conditions

Pogo Mine is located in a cool, dry climate with an annual precipitation of 360 mm (Neuffer et al. 2014) and a mean annual temperature of -2°C. Permafrost is present both in the ground and tailings (Sumitomo 2014), however zones of unfrozen ground and tailings are likely (Nueffer et al. 2014).

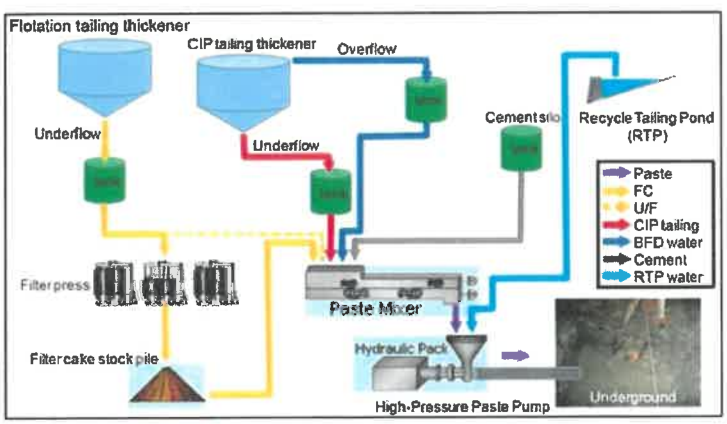
TSF Operations

The plant produces two tailings streams — CIP (carbon-in-pulp) tailings and flotation tailings. The flotation tailings are thickened, then pressure filtered to reduce the moisture content to near optimum (Sumitomo 2014). Part of the filtered flotation tailings are combined with the acid generating CIP tailing sand used for underground backfill, while the remainder is placed in the filtered tailings facility.

The CIP tailings are thickened and combined with cement and filtered flotation tailings to produce a paste for underground backfill.

A process diagram for the Pogo project is shown in Figure II-20.

Figure II-20 Pogo Process Diagram



Source: Sumitomo 2014

Filtered tailings are transported by truck from the filter plant to the filtered tailings facility, where they are placed, spread and compacted.

The TSF consists of a filtered tailings pile with outer shells of waste rock and compacted tailings (Neuffer et al. 2014). Tailings placed in the interior areas of the pile are also compacted, and co-placed with mineralized and non-mineralized waste rock. Perimeter diversions above the pile divert surface runoff around the TSF, while flow-through drains beneath the pile route the remainder. A dam downstream of the tailings pile collects runoff and seepage from the tailings pile and flow through drains. The top of the pile is graded to promote drainage.

TSF Closure

The closure plan for the Pogo filtered tailings facility consists of maintaining a 3H:1V outer pile slope and grading the top of the pile to promote drainage (Neuffer et al. 2014). Erosion will be controlled by routing surface water off the facility in armoured perimeter channels. A soil cover with a growth medium will be used to allow vegetation growth and non-mineralized waste rock will provide erosion resistance. The tailings are considered non-PAG and acidic drainage from the facility is considered unlikely, post-closure.

Reasons for Technology Selection and Realized Benefits

A filtered tailings facility was selected for the Pogo Mine because the topography and foundation conditions were considered unsuitable for a conventional tailings facility (Sumitomo 2014). The steep, narrow valleys would result in a high dam-fill volume-to-tailings storage ratio, and permafrost and alluvial soils in the valley bottom resulted in problematic conditions for dam construction. Filtered tailings are also believed to have reduced the impact to surface and groundwater quality for this site.

REFERENCES

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II-4.7 Mantos Blancos Mine

Mantos Blancos Mine is a 12 000 tpd open pit copper mine operating since 1981 and is located 40 km northeast of Antofagasta, Chile. Tailings are separated into coarse and fine fractions. The coarse tailings are placed in a filtered facility and the fine tailings are pumped to a conventional TSF. The information included in this case study is part of the public domain.

Site Conditions

Mantos Blancos is located in an arid region of Chile with an annual precipitation of less than 50 mm and annual evaporation exceeding 2000 mm. Water is scarce, resulting in an increased desire to minimize water usage.

TSF Operations

Since the start of operations, tailings have been separated into a coarse fraction and a fine fraction using cyclones, after which each stream is dewatered (Bouso and Renner 2005). Fines are thickened and pumped to a conventional TSF. Coarse tailings were initially filtered using vacuum disc filters, however, these were abandoned for vacuum belt filters in the mid 1980s. In 2004, Mantos Blancos replaced the vacuum belt filters with dewatering screens to dewater 50% of the coarse tailings stream (Jewell and Fourie 2015). In 2010, due to the success of the initial vibratory screens, an additional vibratory screen was added.

The dewatering screens are able to achieve solid contents of 80% for the coarse tailings, allowing them to be stacked (although the target solids content has been reduced to 70% which allows the tailings to flow from the deposition point) (Jewell and Fourie 2015). From the dewatering plant, coarse tailings are transported to the TSF and placed using a conveyor system. After placement, the tailings dry further in the arid climate, increasing the strength of the deposit.

Reasons for Technology and Realized Benefits

The primary driver for tailings dewatering at Mantos Blancos is to reduce water consumption (Jewell and Fourie 2015). Switching from vacuum belt filtration to vibratory screens for dewatering coarse tailings has reduced the operating cost for the dewatering system at Mantos Blancos while maintaining similar performance.

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II-4.8 Rosemont Mine

Rosemont Mine is a proposed 75 000 tpd open pit copper mine in Arizona. The design mine life is approximately 21 years, and the filtered TSF design capacity is 587 MT.

Site Conditions

The Rosemont Mine is in an arid climate, with an annual precipitation of approximately 440 mm and an annual evaporation exceeding 1800 mm (Tetra Tech 2009). The maximum credible earthquake adopted for design corresponds to a M7.1 event with a PGA of 0.33g (Newman et al. 2010).

TSF Operations

The proposed tailings management scheme is to dewater the tailings using thickeners, followed by pressure filtration, and then placement of the filtered tailings using a conveyor stacking system.

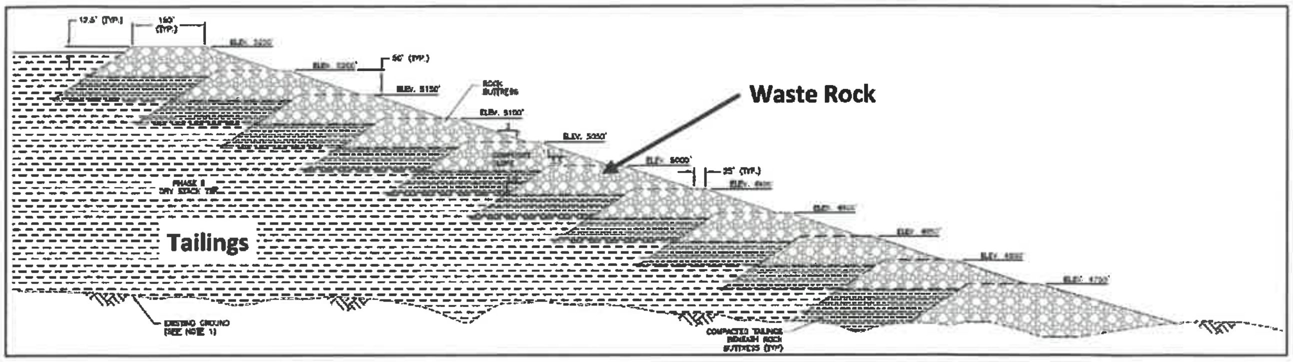
The pressure filters are designed to reduce the moisture content of the filtered tailings to the optimum moisture content of 15%, plus or minus 3%. Moisture contents over 18% were found to result in a significant decrease in strength; soils with moisture contents over 18% would be placed in the centre of the facility and spread, to allow evaporation of excess water, before compaction (Newman et al. 2010).

In the original design, the facility is shown to have a perimeter rockfill zone constructed from waste rock to buttress the filtered tailings; the slope raised using the upstream method to create the cross section shown in Figure II-21. Other designs being investigated would not use an upstream method, but instead, a larger waste rock buttress with a distinct interface, separate from the tailings. Either construction method would allow for progressive reclamation of the outer face of the embankment.

Placement will be through a mobile stacking system, followed by dozer spreading and compaction, if necessary as in the case of the upstream construction method, for structural stability and trafficability (Newman et al. 2010). Stacking will be done in 7.6 m or more lifts, unless compaction is required in areas beneath the rock buttress, resulting in 1.5 m lifts to allow for improved compaction. A secondary conveyor system is planned for times when the primary stacking conveyor is offline, or conveyor moves are planned.

Diversion channels will be constructed to route non-contact water away from facilities. Large stormwater conveyance channels, as well as a drop structure arrangement, are planned to move water off of the tailings facility (Tetra Tech 2012).

Figure II-21 Proposed Rosemont Filtered Tailings Facility Outer Embankment



Source: AMEC 2009 – Drawing 600-CI-909

TSF Closure

The closure plan for Rosemont consists of placing a waste rock cover over the filtered tailings to form a stable landform (Newman et al. 2010). The waste rock cover and buttress will reduce potential for erosion of the tailings from wind and surface water runoff. Storm water control features and shaping of the facility will be used to manage surface runoff.

Reasons for Technology

The primary reason for proposing a filtered tailings for the Rosemont project is to conserve water by improving water recycling. Other benefits include reducing visual impact, reducing footprint, eliminating dam construction, allowing for progressive reclamation and reducing seepage to groundwater (AMEC 2009; Rosemont Copper 2010).

REFERENCES

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Newman, L., Arnold, K. and Wittwer, D. 2010. "Dry Stack Tailings Design for the Rosemont Copper Project." Proceedings from Tailings and Mine Waste 2010: 14th International Conference on Tailings and Mine Waste, Vail, Colorado, October 17-20, 2010.

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II-4.9 Karara Mine

Karara Mine is an iron ore mine in Western Australia producing 35 000 tpd of tailings and in operation since 2013. The design called for tailings to be dewatered and placed in a filtered tailings facility using a conveyor stacking system; however, problems achieving the target throughput have resulted in the need to construct a temporary conventional TSF to store slurry tailings (Gindalbie Minerals 2014). The Karara TSFs are shown in Figure II-22. The information included in this case study is part of the public domain.

Figure II-22 Karara Filtered Tailings Facility and Temporary Slurry Tailings Facility

Source: Google Earth, © 2016 Digital Globe

Site Conditions

Karara is located in an arid climate with an annual precipitation of 310 mm, and annual evaporation of 3875 mm (Hore and Luppnow 2014). The topography is relatively flat with few terrain features. The mean annual temperature is approximately 20°C.

TSF Operations

Tailings are split into a coarse fraction (P80 = 1.5 mm) and a fine fraction (P80 = 0.035 mm), which are dewatered separately to approximately 15% moisture content (Hore and Luppnow 2014). The coarse fraction is dewatered using screens, while the fine fraction is dewatered using pressure filters.

Tailings are conveyed to the TSF and placed using a mobile stacking conveyor system. Advance stacking is used to allow for lifts up to 25 m high. Due to the height of the lifts and the position of the mobile conveyor at the top of the lift, slope failure of the outer face of each lift was a significant design consideration. A required setback from the crest of the outer face was developed for operations to mitigate the risk of a slope failure impacting the mobile conveyor.

TSF Closure

The conceptual closure plan involves regrading the outer slopes of the pile to 3H:1V to create a stable landform (Hore and Luppnow 2014). The final closure cover will consist of topsoil and non-acid generating rockfill to armour the surface.

Reasons for Technology and Realized Benefits

The primary reason for selecting filtered tailings was water recovery, as fresh water is scarce at the project site. Rather than using saline groundwater for processing, which would require washing the final product to remove excess salt, the limited available fresh water is adequate for processing (Hore and Luppnow 2014). Additional benefits of filtered tailings at Karara include having a smaller TSF footprint (due to higher possible stacking heights) and allowing for progressive reclamation of the tailings facility.

During initial operations, there were problems achieving the required moisture content for transporting and placing using the conveyor stacker system, resulting in the need to transport and store slurry tailings (Hore and Luppnow 2014). The fraction of fine tailings requiring filtration was initially much higher than anticipated, resulting in insufficient dewatering capacity. The slurry was initially placed within the footprint of the TSF, creating a weak foundation layer for future advancement of the filtered tailings pile. The weak foundation layer required mitigation, which included preloading, by truck, placement of tailings and farming the tailings surface to promote evaporation, before a lift of filtered tailings could be advanced over it using the conveyor stacking system.

Ongoing limitations with the tailings dewatering system resulted in the need to refurbish the tailings filters and construct a temporary slurry tailings facility to manage tailings in excess of the dewatering capacity of the filters (Gindalbie Metals Ltd. 2014). An additional thickener, additional cyclones and an additional wet tailings facility were planned to store 2.5 years of tailings (as of 2014) to allow the plant to operate at its design capacity with the limitations of the filter system.

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