

Oil Sands Tailings Technology Review

BGC Engineering Inc.

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Oil Sands Research and Information Network

OSRIN is a university-based, independent organization that compiles, interprets and analyses available knowledge about returning landscapes and water impacted by oil sands mining to a natural state and gets that knowledge into the hands of those who can use it to drive breakthrough improvements in reclamation regulations and practices. OSRIN is a project of the University of Alberta's School of Energy and the Environment (SEE). OSRIN was launched with a start-up grant of \$4.5 million from Alberta Environment and a \$250,000 grant from the Canada School of Energy and Environment Ltd.

OSRIN provides:

- **Governments** with the independent, objective, credible information and analysis required to put appropriate regulatory and policy frameworks in place
- **Media, opinion leaders and the general public** with the facts about oil sands development, its environmental and social impacts, and landscape/water reclamation activities – so that public dialogue and policy is informed by solid evidence
- **Industry** with ready access to an integrated view of research that will help them make and execute reclamation plans – a view that crosses disciplines and organizational boundaries

OSRIN recognizes that much research has been done in these areas by a variety of players over 40 years of oil sands development. OSRIN synthesizes this collective knowledge and presents it in a form that allows others to use it to solve pressing problems. Where we identify knowledge gaps, we seek research partners to help fill them.

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REPORT SUMMARY

The search for a viable tailings dewatering technology will intensify as the already large quantities of liquid waste products generated by the oil sands industry grows and tailings storage facilities fill nearer to capacity. BGC Engineering Inc. (BGC) conducted a review of existing tailings technologies for the Oil Sands Research and Information Network (OSRIN).

Over the years, many technologies have been proposed and field tested but they have been rejected for lack of technical or economic feasibility. With no unique and acceptable solution yet in sight, research is now focusing on schemes which utilize more than one technology and combining them into a disposal package.

This report presents an in-depth review of the state-of-knowledge related to oil sands fine tailings treatment technologies. All information is from publicly available sources at the time of writing. The aim of this report is to serve as a fundamental planning document for future research initiatives by OSRIN and other research agencies to support, promote, and improve the oil sands industry's capability to deal with the challenges of fine tailings management.

BGC and OSRIN compiled these references by contacting industry, government, and university researchers, as well as from searches of electronic databases and our own files. We identified 34 oil sands tailings treatment technologies that are discussed and analyzed from a fundamental and practical point of view. The technologies were divided into five groups: (i) Physical/Mechanical Processes, (ii) Natural Processes, (iii) Chemical/Biological Amendments, (iv) Mixtures/Co-disposal, and (v) Permanent Storage.

Considerable research has been conducted to date to develop improved understanding of tailings behaviour, as well as the performance of various treatment technologies so the body of literature in this area is very large. We have collated a large number of references from which this synthesis was developed, and provided these references in a pdf format for more in-depth review by researchers. Researchers are encouraged to undertake their own detailed review of available references to better understand what has been done and learned to date.

CAVEAT

BGC Engineering Inc. (BGC) prepared this document for the account of the Oil Sands Research and Information Network (OSRIN). The material in it reflects the judgment of BGC staff in light of the information available to BGC at the time of document preparation. Any use which a third party makes of this document or any reliance on decisions to be based on it is the responsibility of such third parties. BGC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this document.

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1 INTRODUCTION

BGC Engineering Inc. (BGC) was requested by the Oil Sands Research and Information Network (OSRIN) to describe the state of knowledge related to technologies for oil sands tailings treatment technologies based on available literature. The objective of the scoping study is to help facilitate research and information sharing among a variety of stakeholders and establish an understanding of the status of tailings treatment technology in the Athabasca Oil Sands Region (AOSR).

This report presents a review of the state-of-knowledge related to oil sands fine tailings treatment technologies. All information is from publicly available sources available at the time of writing. The aim of this report is to serve as a planning document for future research initiatives by OSRIN and other research agencies to support, promote and improve the oil sands industry's capability to deal with the challenges of fine tailings management. A companion report produced by BGC in collaboration with OSRIN summarizes emergent technologies for reclamation of tailings deposits in the region (BGC 2010).

BGC staff has been directly involved with oil sands tailings reclamation research, development, design, and operation over the past 15 years and have incorporated this experience into the report.

1.1 Background

Certain areas of the oil sands of northern Alberta are mined and processed for the production of bitumen. The extraction of bitumen from sand using hot or warm water processes produces a slurry waste that is hydraulically transported and stored within surface tailings ponds. The fast-settling sand particles segregate from the slurry upon deposition at the edge of the tailings ponds while the fine fraction accumulates in the center of the pond and settles to become mature fine tailings (MFT). Although most of the water is released and recycled back into the process, 86% of the volume of MFT consists of water (Chalaturnyk et al. 2002). MFT only settles to about 30% to 35% solids content after a few years of placement (Beier et al. 2009). As of 2008, about 750 million cubic metres of MFT exist within the tailings ponds. If there is no change in tailings management, the inventory of fluid tailings is forecast to reach one billion cubic metres in 2014 and two billion in 2034 (Houlihan and Haneef 2008). As of the end of 2009, there are more than 130 square kilometres of tailings ponds in the oil sands region (Government of Alberta 2010). The large volume of MFT requiring safe containment and the vigilant management of capping waters represent a significant management challenge and liability for the industry.

One of the major operational and environmental challenges facing oil sands mining is the separation of water from the fine tailings to strengthen the deposits so they can be reclaimed. A large amount of work over the past 40 years has been undertaken by various research organizations and oil sands mine operators to characterize oil sands tailings materials and to develop techniques for efficiently removing waters. However, much of this work is not easily accessible to the public so these extensive efforts are not widely acknowledged. Some of these scientific and engineering advances are published in diverse journals and specialized conferences making it a challenge to compile the

important literature. Other work has not been published in the open literature but rather is contained in reports that may be more difficult to locate and obtain. Other components of the research information gathered by the oil sands operators from field demonstration tests are proprietary and not accessible to the public. There are dozens of technologies that have been proposed or tested for managing oil sands fine tailings but only a few comprehensive summaries of the technologies have been published (Devenny 2010, Fine Tailings Fundamentals Consortium (FTFC) 1995, Flint 2005, Fuhr et al. 1993, Sims et al. 1984). Many of these technologies have previously been evaluated as being too expensive but might be viable under today's socioeconomic conditions.

This report describes 34 oil sands tailings treatment technologies from a fundamental and practical point of view. The technologies were divided into five groups:

(i) Physical/Mechanical Processes, (ii) Natural Processes, (iii) Chemical/Biological Amendments, (iv) Mixtures/Co-disposal and (v) Permanent Storage.

This report contains the following information:

- A description of the state-of-knowledge regarding dewatering of fine tailings from oil sands mining
- Individual sheets presenting concise information about each technology
- A list of pros and cons of the different dewatering technologies
- Summary tables comparing the different technologies
- A diagram showing the location where each technology fits in the tailings treatment/dewatering process.
- Identification of gaps in the knowledge required to better understand the release of water from sediment within ponds and for creating dry stackable tailings
- Identification of research required to address these gaps
- Figures, pictures and diagrams of some technologies
- A list of publicly-available relevant references for each technology

2 Tailings Explained – From Extraction To Mature Fine Tailings

2.1 Tailings Production

There are currently (as of 2010) four producing oil sands mining and extraction companies in the Fort McMurray area: Suncor Energy Inc., Syncrude Canada Ltd., Shell Canada Ltd. and Canadian Natural Resources Limited. Several more mines are under regulatory review or in the proposal stage. The extraction process used by the Suncor and Syncrude plants is referred to as the Clark Hot Water Extraction (CHWE) Process and is based on the pioneering work of Dr. Karl Clark (Clark 1939, Clark and Pasternack 1932), who used a combination of hot water, steam, and caustic (NaOH) to separate the bitumen from the oil sands. Other operators use slightly different processes.

Figure 1 shows the steps in the process that transform ore to tailings using the CHWE. The figure also shows the relative volume (numbers in parenthesis) of the components of

tailings along the path assuming a final production of one cubic metre of bitumen (relative volumetric numbers taken from Flint 2005).

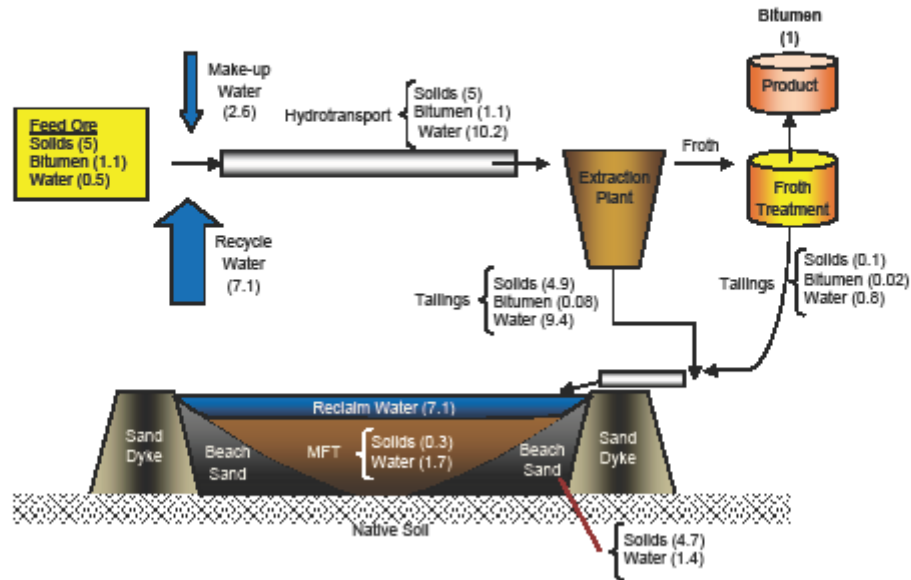


Figure 1. Schematic Of Historical Oil Sands Tailings Management

Processing begins with crushing of the excavated ore. The crushed ore is then conditioned with warm to hot water, steam, and process aides such as caustic (NaOH) or sodium citrate (Shell only) and hydrotransported via pipeline to the extraction plant. Bitumen is separated from the coarse fraction as a floating froth in large gravity separation vessels. The bitumen froth is further processed to remove fine solids. Typical bitumen recoveries range from 88% to 95% depending on oil sands grade and origin. The extraction process produces large volumes of high water content tailings composed of sand, silt, clay, and a small amount of residual bitumen. It is a common practice for the surface mined oil sands industry to define fines as mineral particles smaller than 44 μm . The whole tailings slurry is approximately 45% to 55% solids. Upon deposition, the whole tailings segregate with the sand plus about one-half of the fines dropping out to form dykes and beaches. The remaining water, bitumen, and fines flow into the tailings pond as Thin Fine Tailings (TFT) at approximately 8% solids content (the fines go with the water). After a few years the fines settle to 30% to 35% solids and are referred to as Mature Fine Tailings (MFT). This MFT will remain in a fluid-like state for decades because of its very slow consolidation rate (Kasperski 1992, MacKinnon 1989). Significant portions of the fines remain in suspension after deposition resulting in a tailings management challenge for the industry.

Oil sands tailings are not a consistent product. The volume of solids, fines, and bitumen presented in Figure 1 can vary over a wide range, depending on variations in the ore from the mine, and on various operating and upset conditions within the extraction plant. In

summary, for every unit volume of bitumen recovered, there are 7 to 8 volume units of wet sand and MFT that need to be handled, and 10 volume units of water (recycle and make up) that are pumped around the system (Flint 2005). About 65% of the water used in the extraction process is recycled. The balance – about 3 cubic metres of water per cubic metre of bitumen – is trapped in the tailings pond and the pores of the sand in beaches and dykes (Flint 2005). This water is responsible for continually rising pond volumes. To reduce volumes of water stored and improve trafficability of the deposits for reclamation, these entrapped waters need to be removed with new or improved tailings treatment technologies.

2.2 Basic Tailings Properties

Athabasca oil sands (Cretaceous McMurray Formation) is a mixture of bitumen, mineral matter, and water in varying proportions. The bitumen content ranges from 0% to 19% by total mass, averaging 12%; water varies between approximately 3% to 6% by total mass, increasing as bitumen content decreases; mineral content, predominantly quartz sands and silts, and clay, varies between approximately 84% to 86% by total mass. Clays are present in the McMurray bitumen-containing deposits in thin discontinuous clay layers (Chalaturnyk et al. 2002).

The major clay components of the McMurray Formation are 40% to 70% kaolinite, 30% to 45% illite with up to 10% mixed layer illite/smectite (Chalaturnyk et al. 2002). It is believed that illite in and mixed layer clays are largely responsible for the processing and compaction problems in oil sands extraction and fine tailings disposal. The more active clays, perhaps somewhat degraded by weathering or the action of caustic soda, and coated with bituminous residues appear to be the main cause of the gel-like structure formation in the tailings and for the ion exchange mechanism in the tailings ponds (Chalaturnyk et al. 2002).

The fundamentals of the formation of low density fine tailings deposits are still poorly understood, despite enormous research efforts. It is known that clay minerals, in the presence of caustic soda, possess an enhanced negative surface charge which promotes dispersion of the particles, inhibiting their sedimentation and consolidation. Dispersion of the clays, which is necessary for efficient bitumen extraction by flotation, prevents rapid dewatering (sedimentation and consolidation) of the tailings clays. Adding sodium ions (as caustic) to the oil sands extraction process exacerbates this undesirable condition as far as tailings disposal is concerned.

The dispersant effect of these monovalent sodium ions can be counteracted and controlled to some extent by the addition of divalent calcium ions. This cation exchange process and the affinity of calcium ions for the clay surface play an important role in many all tailings treatment strategies (Mikula et al. 2008).

The water holding capacity of MFT and the slow consolidation rate is governed by the surface properties of the minerals. The forces that affect colloidal particles in suspension and determine the final settled volume, hydraulic conductivity, and strength of the material have four essential components (FTFC 1995): electrostatic, steric, Van der Waals, and hydration. A knowledge and understanding of these components will help explain why so many conventional solutions to the clay slurry disposal problem have

been unsuccessful in the oil sands industry. There are a number of important knowledge (technology) gaps (Flint 2005) identified in the oil sands industry including:

- Quantification and modeling of the fine tailings dispersion
- MFT morphology and characteristics
- Sand, clay, organics and water interaction in tailings
- Role of chemical additives in modifying tailings properties.

Some basic geotechnical properties of MFT are summarized as follows (FTFC 1995):

- The mean particle size of the fine tailings is between 5 μm and 10 μm .
- The average solids content of MFT is about 33% which is an average void ratio of 5.
- The hydraulic conductivity of the MFT is in the range of 1×10^{-6} to 1×10^{-9} m/s which accounts for its slow rate of consolidation.
- The liquid limit ranges from 40% to 75%.
- The plastic limit ranges from 10% to 20%.
- The viscosity varies from 0 to 5000 cP and it increases as time passes (after it is disturbed or deposited). This time dependent behaviour is termed thixotropy.
- MFT shear strengths are typically much less than 1 kPa (i.e., it acts as a fluid).

2.3 Objectives in Treating Tailings

The main objective in treating the oil sands tailings is to remove water so that a trafficable load-bearing surface can be produced within a reasonable time-frame to allow subsequent reclamation, and the resulting deposit is no longer mobile – it will no longer require dam-like containment.

The number of stages used to dewater the tailings, and the timing thereof, depends on several factors:

- Technical feasibility (does it work?)
- Dewatering efficiency
- Optimizing moisture content for pumping or other types of transport
- Winter operation
- Timely reclamation
- Operational practicability (is it practicable on a large scale?)
- Cost-effectiveness (is it affordable?)
- Robustness (can it deal with the variability in the tailings consistency)

The optimal treatment strategy may involve several stages of dewatering, using a number of different technologies. A long list of techniques have been conceived, developed and tested over a period of many years and by a variety of industries with similar problems. It quickly becomes apparent that, technically, the area of dewatering industrial sludges, slimes and mine waste tailings resembles that of a well-ploughed field and the probability of developing an entirely new technique successfully is becoming less likely as time advances. These different technologies are discussed further in Section 3.

2.4 Tailings Challenges

Tailings management practices at the operating plants over the last four decades have resulted in large inventories of MFT requiring long term storage within fluid containment structures (Houlihan and Haneef 2008). This inventory will be further referred to as *legacy tailings*. Although less than 10% of the total bitumen reserves in the Athabasca deposit are amenable to surface mining (Government of Alberta 2010), this method of extracting bitumen from the oil sands is currently the most economic and may remain so for some time.

Water management is also an issue for these mine sites in addition to managing large volumes of fluid fine tailings. The mines are currently operating under a zero-effluent discharge policy preventing release of accumulated process-affected water. Tailings management is thus intimately related to the site-wide water balance and the provision of reclaim water to the extraction plant. Continual recycle of process water (tailings release water) to the extraction plant has led to a build-up of dissolved ions within the recycle water. Elevated ion concentrations can lead to various operational problems including poor extraction recovery, scaling/fouling of piping and equipment (Beier et al. 2009) and create future environmental problems for water release and treatment. Thus fresh make-up water must be brought onto the sites to reduce the ion concentrations to specified levels.

Oil sands tailings also contain a residual amount of un-extracted bitumen which impacts the characteristics and behaviour of the tailings, and introduces operational complexities (Sobkowicz and Morgenstern 2009).

Due to the abundance of ore deposits, many of the mine leases are highly constrained in available surface area on which to dispose of waste. Overburden dumps, tailings ponds, dedicated disposal areas (DDA), thin lift dewatering areas, and other waste disposal facilities all compete for limited out-of-pit and in-pit space. For this reason, considerable research has been conducted in recent years in an effort to identify ways of reducing or eliminating the environmental concerns associated with reclamation of these wastes.

3 TAILINGS TREATMENT TECHNOLOGIES

3.1 General

The technologies available for dewatering oil sands tailings are presented here for the purpose of understanding them better; in particular for understanding why many have been judged inadequate and have failed to gain acceptance commercially. Thirty-four technologies are discussed and analyzed from a fundamental and practical point of view.

The technologies have been divided into five groups:

- Physical/Mechanical Processes
- Natural Processes
- Chemical/Biological Amendments
- Mixtures/Co-disposal
- Permanent Storage.

The following information is provided for each technology:

- A brief description of the technology
- Pros, including benefits and advantages
- Cons, including challenges and disadvantages
- Knowledge gaps: this includes an assessment of what is missing, what research needs to be conducted to take the technology to the next level or stage. The information provided is based on available published literature and the authors' opinions
- Stage of Technology: providing an assessment of the maturity of the technology. Four stages are considered: Basic research, Applied research and demonstration, Commercial demonstration, and Mature (operates commercially).

These stages are not well defined transitions but are notional in concept. Effort or costs are relatively modest in the early stages, where basic and applied research are characterized by small scale experimentation to advance knowledge or prove concepts. Some refer to this stage as developing “pre-competitive” or “enabling” technologies. When the understanding of a given technology has reached a certain level, work begins in the development phase to focus on means to commercialize the technology, and this moves into the much more costly work, often with intensive piloting and large scale prototypes. In the context of the work under review here, this stage is often funded by the eventual user because the development of marketable commercial know how and other intellectual property is involved, sometimes protected by new patents and the results are consequently sometimes kept confidential. Brief descriptions of these stages (modified from Flint 2005) are presented below.

It should be noted that basic research program may cost a hundreds of thousands of dollars, pilots several million dollars, and commercial implementation hundreds of millions of dollars. Tailings management over the life of a mine will cost several billion dollars. Failure of a tailings technology may have even more costly impacts on production or the environment. Accordingly, only a few technologies reach the pilot stage, and fewer to the commercial scale; there are often considerable difficulties in scaling technologies that work well in the lab.

Basic research is often performed in universities, as well as government labs and industry research labs. The intent of the work does not necessarily have any defined commercial intent but is designed to extend the frontiers of knowledge. Basic research

provides improved understanding of the processes and development issues towards the more commercial stage of development. Basic research is characterized by experimentation and frequent failure or dead ends.

Applied research and demonstration occurs when an individual industry player (or a consortium) sees a potential commercial value and starts to fund additional research to help accelerate scientific understanding but now focused toward specific commercial objectives. This stage is normally responsible for the most accelerated phase of the technology development or understanding. Field pilots may be run as part of this stage.

Commercial demonstration: During this stage of research, technologies typically move from pre-competitive status towards the potential for commercial application and individual industry players will move to development to meet commercialization timeframes. This work is devoted to development, often with large prototype operation.

Mature (operates commercially) is when the technology operates commercially at full scale.

We have classified each of the 34 technologies according to this scale for oil sands applications. In some cases, we have indicated where this technology is well developed outside the oil sands industry.

Summary tables (11x17" sheets) have been prepared to help the reader make comparisons among the different technologies (see [Appendix 1](#)). Also, individual summary sheets (8½x11"), one for each technology, were prepared to present concise information about each technology, including a list of references related to each technology (see [Appendix 2](#)).

Sobkowicz and Morgenstern (2009) developed a diagram titled *Tailings Technology Road Map* illustrating a variety of technologies that are available for dewatering/treating tailings. The diagram shows the possible paths that the tailings may take from the point where they are generated to their permanent storage. A copy of the diagram is attached in [Appendix 3](#). We added in the diagram the location where we believe each of the 34 technologies reviewed in this report fit in the dewatering/treatment process.

Figures, pictures, and diagrams of some technologies are included in [Appendix 4](#) as visual aids to provide the reader a clear picture of these technologies.

3.2 Physical/Mechanical Processes

Physical/mechanical processes involve the use of a variety of technologies to separate the water from the solids.

3.2.1 Filtered Whole Tailings

This technology consists of filtering the whole (unaltered) tailings stream. Filtration is one of the most traditional methods for solid-liquid separation. It has been widely used in other industries.

Filtering can take place using pressure or vacuum force. Drums, horizontally or vertically stacked plates and horizontal belts are the most common filtration plant configurations. Pressure filtration can be carried out on a much wider spectrum of

materials though vacuum belt filtration is probably the most logical for larger scale operations.

In the mid-1990s, pilot-scale tests were conducted on a different bitumen extraction process known in Alberta's oil sands industry as the Bitmin Process (FTFC 1995). Experiments were carried out to determine if direct vacuum filtration of the whole tailings would work. Many of these experiments were unsuccessful, as it was found that the coarse particles would naturally settle relatively quickly and would build up a thick porous filter cake however the slower settling fines would gradually settle onto the surface of this cake and blind it (creating a thin film of very low hydraulic conductivity material), thereby effectively shutting off filtration. Due to the extremely large volume of tailings to be processed and lack of regulatory pressure and incentive in implementing dry tailings disposal, the filtration has never been implemented at the mature stage. However, recently, it has been reconsidered as an option for tailings disposal by several oil sands companies. Large surface areas per unit production are typically required.

The hydraulic conductivity (and hence the filtration) of the tailings can be enhanced with coagulants or flocculants. Coagulated and flocculated particles are larger and form a less dense and more porous and permeable cake and therefore allow faster filtration.

Xu et al. (2008) conducted simple laboratory-scale filtration tests to evaluate the filterability of the oil sands tailings and to generate a parameter that can be used in filtration scale-up. They indicated that the fines content plays a critical role in filtering the oil sands tailings and that it is impractical to filter original tailings with more than 4% fines without using flocculant. The average fines content of the whole tailings stream is about 18% and filtration of this type of tailings (even with flocculant aids) seems challenging and requires a large filtration area.

The use of pre-coat materials on the filter media can help optimize filter performance. The coating of an inert material such as diatomite (or a sand blanket), protects the filter cloth septum from blinding and facilitates cake release. However, this technique may not be suitable for high volume, low product value applications, as it adds to operating costs considerably.

Pressure filters consisting of horizontally or vertically stacked plates and vacuum filters consisting of drums and horizontal belts are the most common filtration plant configurations. Pressure filtration can be carried out on a much wider spectrum of materials.

Filter cake is produced at sufficiently high solids content to truck or convey to a reuse or final disposal site. The equipment selection to transport the filtered tailings is a function of cost. Placement in the facility can be done by a conveyor radial stacker system or trucks depending upon the application and the design criteria. As with most mechanical dewatering systems the need for settling basins, return water systems, and containment area reclamation, as well as the piping and pumps to the settling area is minimized or eliminated.

The main issue associated with the placement of the filtered tailings by truck is usually trafficability. The filtered tailings are generally produced at or slightly above the optimum moisture content for compaction as determined in laboratory compaction tests

(Proctor Tests). Addition effort to get closer to the Proctor optimum moisture content can increase operational cost of a filtering system significantly. This means that a construction/operating plan is required to avoid trafficability problems. It may be possible to place the filtered tailings in a loose state, but care must be taken to avoid flowslides upon first time wetting, or to design and control access to restricted areas.

Syncrude (2008) conducted a tailings technology assessment for the purpose of selecting a tailings management strategy and corresponding technology platform for their mine leases. Syncrude (2008) eliminated filtration of whole tailings technology due to concerns and uncertainty about the high capital and operating costs.

Filtered tailings sand has a high value for an oil sands operation as it is easy to compact into dykes and dumps, has fewer ions to leach out due to its partial saturation at placement, and is relatively easy to reclaim.

Pros

- Requires a small footprint for tailings storage.
- High recovery of process water.
- Filtration produces “dry tailings” for stacking requiring no dam for retention.
- Can be compacted.
- Attractive to regulators.
- Ease of progressive reclamation and closure of the facility, amenable to concurrent reclamation.
- Low long-term liability in terms of structural integrity and potential environmental impacts.
- Use of flocculants improves filterability significantly.
- Dry tailings can be stacked at slopes greater than 10%.
- No long-term consolidation settlements are expected because of the low moisture content. (Some post reclamation elastic or collapse settlements may still occur depending upon the density of the final deposit).

Cons

- The process is costly due to the large amount of coagulant used and the high capital and operating costs for filtration equipment.
- Filtered tailings are no longer pumpable (low water content) and they need to be transported by conveyor or truck.
- Often more expensive per tonne of tailings stored than conventional slurry system, costly to truck and compact.
- The residual bitumen from extraction can clog the filters.
- Target only new tailings, not legacy MFT.

- Some reports indicate it is impractical to filter whole tailings with more than 4% fines without using flocculant.
- Challenging winter operations.
- Water quality may be affected by flocculants (if used).

Knowledge gaps

- Optimize various polymer parameters: ionic type, charge density, molecular weight and dosage for a given tailings composition (fines content).
- Further study the impacts of polymers on water quality.
- Evaluate the filterability of tailings and filtration performance.
- Evaluate at large scale.
- Investigate filtration systems that can deal with bitumen fouling and high fines content.

Stage of technology

- Applied research (mature in several non-oil sands tailings industries).

3.2.2 Cross-flow Filtration of Whole Tailings

Cross-flow filtration gets its name because the majority of the feed flow travels tangentially across the surface of the filter, rather than into the filter. The main advantage of this is that a thickness of the filter cake (which can blind the filter) is substantially limited during the filtration process therefore the cross-flow filtration can be operated for a longer time compared to the other filtration methods. It can be a continuous process.

In cross-flow filtration, the feed is passed across the filter membrane (tangentially) at positive pressure relative to the permeate side. A proportion of the material which is smaller than the membrane pore size passes through the membrane as permeate or filtrate; everything else is retained on the feed side of the membrane as retentate. With cross-flow filtration the tangential motion of the bulk of the fluid across the membrane causes trapped particles on the filter (cake) surface to be rubbed off. This means that a cross-flow filter can operate continuously at relatively high solids loads without blinding.

This technology is currently being investigated at the University of Alberta. Several experiments have been carried out to assess the effect of filter membrane property, tailings composition, tailings solids content and residual bitumen on the performance of cross-flow filtration of oil sands whole tailings (Zhang et al. 2009).

Pros

- Higher dewatering rate is achieved by limiting cake thickness.
- Process feed remains in the form of a mobile slurry, suitable for further processing.
- Solids content of the product slurry may be varied over a wide range.
- No chemical additive is required therefore no changes in the water chemistry.

- Target both new tailings and legacy MFT.

Cons

- Performance may be affected by the variability of whole tailings composition (fines content may affect performance).
- Presence of residual bitumen may plug the membrane pores affecting performance.

Knowledge gaps

- It was found that increasing slurry velocity during cross-flow filtration operation can improve filtrate rate. Further confirmation on influence of transmembrane pressure and tailings slurry velocity on the performance for various feeds (e.g., various fines content) is required.
- Define variation of permeate flux and quality as well as cake characteristics along pipe length (Ifill et al. 2010).
- Investigate whether this technology can be used effectively on TFT and MFT.

Stage of technology

- Basic research.

3.2.3 *Filtered Coarse Tailings*

This technology consists of filtering and dry stacking of the coarse fraction (cyclone underflow tailings (CUT)) of the tailings slurry. Variants include adding some fines to the mix prior to filtration. CUT are usually stripped of some fines and water and are not too dissimilar, although somewhat more variable, in composition than composite/consolidated tailings (CT) (Sobkowicz and Morgenstern 2009).

Development of large capacity vacuum and pressure filter technology has presented the opportunity for storing tailings in an unsaturated state, rather than as conventional slurry or in a paste consistency associated with thickened tailings.

Xu et al. (2008) found that the filterability of the coarse oil sands tailings (about 12% fines) was relatively low. However, after the fines were flocculated with the coarse particles to form uniform flocs the filterability was improved by several orders of magnitude. The results demonstrate that filtration of the flocculated coarse tailings to produce the “dry” stackable tailings may be viable.

Similar to the previous technology (Section 3.2.1), filtered tailings are transported by conveyor or truck and placed, spread and compacted to form an unsaturated, dense and stable tailings stack (often termed a “dry stack”). Dry stack facilities don’t typically require a dam for a retention structure and as such no associated tailings pond. Each project needs to assess the potential applicability for filtered tailings based upon technical, economical, and regulatory constraints. Compaction is required to avoid creating potentially mobile deposits upon first time wetting.

Benefits and challenges of this technology are similar to the filtered whole tailings technology and they will not be repeated here. However, additional pros and cons are described below:

Pros

- Applicable without flocculants when fines content is less than 4% (Xu et al. 2008).
- Viable method after flocculation for tailings with about 12% fines, which correspond to the sediment underflow from gravity settlers such a Primary Separation Vessel (PSV) (Xu et al. 2008).
- Low fines content can cause faster filtration and less blinding.
- Operational costs are reduced if flocculants are not required. This may be only practical with low fines content (<4% fines).
- Results in a useful construction material with lower ionic contents.

Cons

- Need to remove the fine fraction using a hydrocyclone or other methods.
- Compaction or special handling procedures required for deposits.
- High transport and deposition costs.

Knowledge gaps

- Same as filtered whole tailings technology in Section 3.2.1.

Stage of technology

- Basic research and applied research and demonstration.

3.2.4 *Filtered Thickened Fines Tailings*

This technology includes filtration and dry stacking of thickener underflow (predominantly fines). Other fine tailings streams may include centrifuge fine tailings and MFT. This technology has been proposed but it seems impractical due to the high fines content. The fines content of fine tailings can be as high as 96%. Bench-scale tests (Xu et al. 2008) have demonstrated that filtering flocculated fine tailings with fines content greater than 18% are very challenging and perhaps impractical at large-scale.

Pros

- Address legacy MFT.
- Generate dry stack tailings with the benefits described in the previous technologies.

Cons

- Filterability is relatively low, due to the high fines content.

Knowledge gaps

- Need to identify polymers (flocculants, coagulants) that can deal with high fines content tailings and make the filtering more effective.

Stage of technology

- Basic research.

3.2.5 *Centrifuge fine tailings*

A centrifuge applies up to thousands of times the force of gravity to extract fluid from material. The outlet stream yields solids content of about 60% (Devenny 2010). The overflow stream yields water, bitumen, and a minor amount of fines. Centrifuges are used extensively in oil sands froth treatment but they have not been used to process MFT commercially. Centrifuge technology to produce dry tailings was evaluated in the past with some success but the cost was unacceptable at that time. A better appreciation of the costs of MFT storage has prompted a re-evaluation of this technology. The use of additives to improve centrifuge performance has significantly improved the results which can be achieved. Centrifuge technology has been developed at bench scale at CANMET (Mikula et al. 2008, 2009) on Athabasca oil sands fluid fine tailings and has been successfully piloted in demonstration plants on Syncrude's MFT (Fair 2008). However, testing at full scale is needed to properly evaluate the potential of this technology.

In the case of the large scale oil sands operations, implementation of a dry stackable tailings management option based on centrifugation of the fluid fine tailings will require verification of several operational issues. These include the centrifuge performance of higher clay to water ratio fluid fine tailings, as well as the logistical issues around transporting a solid rather than slurry tailings and the trafficability of the resulting deposit, which is likely to start near its liquid limit in terms of consistency.

Syncrude sees MFT centrifuge dewatering as a two-step process (Lahaie 2008). The first step involves MFT dewatering using horizontal solid bowl scroll centrifuge technology with flocculant addition, forming two streams: centrate - i.e., relatively solids-free water having 0.5% to 1% solids, returned to the tailings water system for recycle; and cake, a 60% solids soft soil material capturing greater than 95% of the solids. Cake is roughly half the volume of the original tailings.

The second step involves subsequent dewatering of the cake by natural processes; consolidation, desiccation and freeze-thaw via 1 to 2 m thick annual lifts, delivering a trafficable surface that can be reclaimed.

Suncor and Syncrude jointly evaluated available centrifuges and tested a small 5 tonne per hour centrifuge as a means to process MFT (Suncor 2009). The underflow from the centrifuge process was deposited as a paste comprising primarily fines with a solids content of 55% to 60% solids to in-pit beaching areas where material could be reclaimed in place.

The process appeared promising and Suncor considered a larger scale field trial of this technology in its application (Suncor 2009) for the Tailings Reduction Operations (TRO) Experimental Facilities. The primary issue with this technology was the capability to scale up centrifuge sizes from those currently available to units with sufficient capacity to

cost-effectively treat the volumes of MFT involved. Suncor withdrew the centrifuge component of the proposed experimental facilities because of unfavourable economics of the process coupled with the conclusion that MFT drying was a superior technology as demonstrated by the continuing success of the MFT drying process at the Pond 8A test facility. Suncor is continuing to monitor industry development of this technology. Specifically, Suncor will monitor Syncrude's work on the centrifuge through current data sharing agreements.

Syncrude began bench trials of this technique in 2005 (Lahaie 2008), progressing to a two-month-long test in 2008 focusing on MFT flocculation and the centrifuge process, as well as on preliminary cake-transportation assessment involving conveyors, positive displacement pumps and a pipeline. Two "pods" of oilfield-scale centrifuges were operated in parallel, using two Alfa Laval Lynx 40 (nominal 400 mm diameter) machines running in parallel to provide centrifuge cake for transportation assessment and bulk materials for geotechnical and environmental studies. Another MiSWACO 518 centrifuge (nominal 355 mm diameter) was used to gain MFT flocculation and MFT centrifuge process understanding, flocculant optimization studies and centrifuge operational parameter assessments.

These tests showed promise. The technology is robust, with solids throughput on target and high solids capture in cake. Centrifuge cake transportation and deposition results also were encouraging and equipment scoping studies were planned for 2009, with centrifuge scale-up progressing from the nominal 400 mm to 1,000 mm diameter machines (Lahaie 2008).

Commercial scale demonstration of this technology is scheduled to begin in 2012 (Syncrude 2008) with annual plant MFT volume inputs in the range of 1.5 million cubic metres of MFT, using MFT inventories as feedstock. Syncrude proposes to place the centrifuge cake deposit on a tailings beach for the demonstration period. Depositing the centrifuged MFT on a beach would allow easy access for re-handle of the material if required. In 2015, centrifuged MFT deposition will begin in the North Mine.

Pros

- Requires relatively small storage area.
- Recover large amount of process water.
- Insensitive to bitumen fouling.
- Addresses legacy MFT.
- The solid bowl centrifuge is a continuous feed operation typically requiring reduced labour and operator effort.
- This technology is also noted as being the best technology for most oil, water, and latex sludge streams. Filter cake can be produced at a sufficiently high solids content to truck or convey to a reuse or to a final disposal site.
- As with most mechanical dewatering systems, the need for settling basins, return water systems and containment area reclamation, as well as the piping and pumps to the settling area is minimized or eliminated.

- Resulting deposit may be trafficable to specialized equipment and suitable for hydraulic sand capping or reclamation.
- Allows processing of tailings that is decoupled from the extraction process.

Cons

- High upfront capital and operating costs.
- There may be issues with scale-up and trafficability (soft ground conditions can impede progress).
- Transporting centrifuged cake may be challenging.
- Does not target new fines.
- Operation of a centrifuge requires a higher skill level and a more experienced operator.
- Requires a greater amount of electric power compared to filter press and belt press technologies.
- The solid bowl centrifuge functions as a secondary dewatering step necessitating a pre-thickening step; usually accomplished by a conventional thickener or clarifier. This technology must be considered a step in a more complex process and is not applicable as a stand-alone dewatering system.

Knowledge gaps

- Flocculant optimization.
- Cake transportation issues: conveyor and positive displacement pump.
- Need to evaluate centrifuge operational parameters and performance.
- Centrifuge scale-up studies.
- Need to further assess dewatering of centrifuged cake by natural processes and determination of optimal lift thickness.

Stage of technology

- Applied research and demonstration.

3.2.6 *Thermal Drying MFT*

This technology consists of heating MFT in an oven/kiln to reduce the moisture content of MFT. Thermal drying can remove water from fines to a significantly higher degree than all other dewatering processes. Solids content reaching 90% is attainable but the slurry is typically dewatered to a minimum of 18% to 20% solids before it is directed to the drying facility (BCI 2007). This technology has not been pursued due to its high cost, but such a cost may form an upper bound for fine tailings treatment.

Pros

- Thermal MFT drying eliminates water and diminishes the volume of the MFT by a factor of 4 to 5.

- It lowers the transportation cost and facilitates storage.
- Rapid removal of moisture in MFT.

Cons

- Thermal drying is noted for its high-energy demand.

Knowledge gaps

- Environmental impact from vapor generated from the thermal drying.

Stage of technology

- Basic research.

3.2.7 *Electrical Treatment*

The electrical treatment technology is the application of a direct current (DC) electric field to a clay slurry. The electrical field causes negatively charged clay particles to migrate to the positive (anode) electrode, resulting in accelerated sedimentation. Electrical methods have been investigated for their possible use to dewater MFT (Flintoff and Plitt 1976, FTFC 1995). The principles of electrokinetic dewatering are electrophoresis, dielectrophoresis, and electro-osmosis (Shang and Lo 1997).

Electrophoresis is the movement of electrical charged particles in a direct current (DC) electric field; dielectrophoresis is the movement of the particles in a non-uniform electric field (can be either AC or DC); and electro-osmosis is the water flow in porous media induced by a direct current (DC) electric field (Shang and Lo 1997).

Electro-osmosis is not applicable in a dilute clay suspension in which soil particles move freely in water and there is no porous grain skeleton to act as capillaries. In this case, the effect of electro-osmosis is negligible. With the increase of solid concentration during sedimentation, there is a transient period during which a dilute clay suspension (solid-in-water) is gradually converted to a porous clay mass (water-in-solid). During the transient period, electro-osmosis becomes increasingly significant until it replaces electrophoresis as the dominating electrokinetic phenomenon. The relative significance of electrophoresis and electro-osmosis in a sedimentation process has not been quantitatively defined (Shang 1997b).

Attempts to use electro-osmotic techniques to dewater phosphate clays in Florida date back over 20 years. While the technology "would appear to have promise" (U.S. Department of the Interior 1983) it was "not considered commercially feasible" except, under special circumstances because of the slow dewatering rate of the clay wastes. Significantly increasing the dewatering rate was possible but involved prohibitive energy costs.

In recent years there has been an interest in the possible combination of surcharge preloading, vertical drains and electro-osmosis to consolidate clay soils (Fourie 2009, Mohamedelhassan 2008, Shang 1998, Shang et al. 2009).

There are no instances of very large-scale implementation of the concept in this type of application. Possible reasons for this were suggested by Shang and Lo (1997) as including high power consumption, indiscriminate use of the technique and an

improperly designed operating system, problems with corrosion of the anodes (and metal loading to the tailings), and difficulty in collecting and removing water drained to the cathode. Intrinsic to these difficulties may be a limited understanding of electrokinetics.

Electrical treatment is considered an “emerging technology” with little full-scale information available.

Pros

- Electrophoresis can be employed in the treatment of slurries.
- Electro-osmosis becomes significant when the slurry is gradually converted to a porous soil mass.
- Can be used in conjunction with surcharge loading and wick drains.
- Can also be combined with conventional filter presses.

Cons

- Involves very high energy costs.
- Applicable to relatively narrow range of materials (primarily silts).
- Difficulty in removing supernatant liquid.
- Problems with corrosion of the electrodes.
- Considered an “emerging technology” with little-to-no plant-scale use or information available.

Knowledge gaps

- Need better understanding of electrokinetics.
- Need to research problems with corrosion of the electrodes.
- Collection and removal of water drained to the cathode.

Stage of technology

- Basic research.

3.2.8 *Blast Densification*

Blast densification or explosive compaction is a densification technology that is predominantly used by the geotechnical community to pack loose, saturated, medium to coarse materials. Explosive compaction is carried out by setting off explosive charges in the ground. The energy released causes liquefaction of the soil close to the blast point and causes cyclic straining of the soil. This cyclic strain process increases pore water pressures and provided that strain amplitudes and numbers of cycles of straining are sufficient, the soil mass liquefies (i.e., pore water pressures are temporarily elevated to the effective vertical overburden stress in the soil mass so that a heavy fluid is created) (Gohl et al. 2000). Liquefaction of the soil following by time-dependent dissipation of the excess water pressures causes re-consolidation within the soil mass. This re-consolidation happens within hours to days following blasting, depending on the hydraulic conductivity of the soils and drainage boundary conditions, and is reflected by

release of large volumes of water at the ground surface or up blast casings. "Short term" volume change is also caused by passage of the blast-induced shock front through the soil mass. Close to the charge detonation, the hydrodynamic pressures are large enough to cause compression of the soil-water system even though the bulk compressibility of the system is relatively small (Gohl et al. 2000).

Blast densification trials were conducted attempting to densify loose tailings sands in a tailings dike at Suncor Oil Sands (Fordham et al. 1991) and also at Syncrude.

Densification of the sand was undertaken to reduce the potential for liquefaction.

Blasting was considered to be a suitable method, based on a series of blast densification trials to determine acceptable drilling and loading techniques, the effects of blasting on nearby structures and charge density. Time dependency of the densification of the sand was observed based on cone penetration test (CPT) measurements made immediately after blasting and again four months later. Initially, the sand appeared to be as loose or looser than prior to blasting. However, after four months, the increases in the density of the sand were observed. The time dependency was believed to have been due to re-establishment of intergranular frictional contacts among sand particles.

Blast densification of fluid fine tailings to temporarily break the thixotropic bonds and allow rapid consolidation of thick tailings deposits has recently received some interest.

Pros

- Used to pack loose, saturated, medium to coarse sands.
- Eliminate the potential for liquefaction.

Cons

- Densification is not an instantaneous phenomenon.
- Possibility to damage nearby retention structures (dykes, dams).
- Requires monitoring (surveying, pore pressure).

Knowledge gaps

- Need to understand time dependency process.
- Behaviour of fine tailings during blast densification.

Stage of technology

- Basic research.

3.2.9 Wick Drains

Consolidation of soft compressible soils involves the removal of excess pore water from the soil. This is traditionally done by applying a surcharge or preload on the construction area to squeeze out the water. Unfortunately, compressible soils often also have very low hydraulic conductivity and as such, water is not easily nor quickly removed and the consolidation time is unacceptably long.

Prefabricated vertical drains (also called wick drains or band drains) greatly facilitate the dewatering process by providing a suitable conduit to allow the pore water to escape very

quickly. Vertical wicks can be economically installed at close spacing, shortening the flow path of the water, and thereby expediting the consolidation process. Consolidation of soft cohesive soils using wick drains can reduce settlement times from years to months.

In 2009, Suncor conducted field trials of vertical wick drains installed in very high fines, low density tailings in Pond 5 (Wells and Caldwell 2009). Preliminary findings indicate that vertical drains are capable of dewatering very soft fluid tailings within oil sands CT ponds. Wells and Caldwell (2009) reported that laboratory testing was undertaken at the University of British Columbia to evaluate the potential for Suncor's soft tailings to clog the geotextiles commonly used in wick drains. The laboratory testing indicated that there was no evidence of clogging of nonwoven geotextiles with apparent opening sizes (AOS) of 90 μm and 210 μm and that there was some evidence of very minor piping with woven geotextiles with an AOS of 300 μm .

Suncor is currently conducting field trials of wick drains in CT deposits.

Pros

- Accelerate the consolidation process reducing settlement times from years to months.
- Allows an accelerated placement of a final reclamation cover.
- Address legacy MFT/CT volumes.

Cons

- Wick drains may not retain their shape and integrity over time due to large settlement.
- As water is drained from the tailings, solid-like tailings begin to form around the wick drains and hence the hydraulic conductivity of these materials begins to impact flow rates in the wick drains.
- Clogging of wick drains.
- May require surcharge loading.
- Difficulty getting equipment onto the soft deposit.
- Costly due to close spacing of wick drains.

Knowledge gaps

- Need to conduct large-scale tests to assess viability of this technology.
- Evaluate clogging of the wick drains in the field.
- Evaluate wick drain performance in conjunction with surcharge loading to accelerate dewatering.
- The mechanics of wicks is not well understood in materials that do not exhibit effective stress (high fines CT and MFT).

Stage of technology

- Applied research and commercial demonstration.

3.2.10 Surcharge Loading

Surcharge loading offers a time-tested procedure for accelerating the consolidation and dewatering process and increasing the rate of strength gain of poorly-consolidated clay soils, but the low undrained shear strength of high water content tailings usually makes it difficult to apply the surcharge without causing a stability failure and consequent mud wave. Typically a strong geotextile or geogrid/geotextile combination is used to allow placement of thin lifts of surcharge.

Suncor (2009) is currently conducting field trials of surcharge loading (sand or additional coke layers) in conjunction with wick drains in CT deposits.

Pros

- Accelerates the dewatering process.
- Coke cap can be placed on top of MFT by sub-aqueous discharge.
- Use of geosynthetics can prevent mud wave but it is costly.
- Can be used with wick drains to accelerate consolidation.
- A few feet of surcharge is necessary to form a pad on which equipment can operate.
- Drainage blanket installed at the bottom can accelerate the dewatering process by applying a partial vacuum to the system.
- Allows for trafficability of the deposit.

Cons

- Difficult to place the surcharge cap on top of the MFT.
- Stability issues during cap placement (mud waves).
- Clogging of geotextile separation blankets remains a concern.

Knowledge gaps

- Evaluate floating loading using geosynthetic reinforcement.
- Evaluate placement techniques for optimal implementation.
- Evaluate performance with wick drains to accelerate consolidation.

Stage of technology

- Applied research and commercial demonstration.

3.2.11 CT under MFT

Unlike the co-disposal approach, which involves mixing of tailings, this technology using CT placed beneath MFT was proposed to improve the CT release water quality and the solids densification rates of both CT and MFT.

Synchrude conducted a pilot-scale field demonstration test in 1995 to study this technology (referenced by Luo 2004). The purposes of this CT beneath MFT deposition were to improve the CT release water quality and MFT densification rate, and to see if the CT densification rate will be adversely affected. The field demonstration test indicated that the CT beneath MFT deposition initiated changes that were beneficial to tailings disposal, with respect to the release water quality and densification rates of both MFT and CT.

Luo (2004) conducted research using laboratory-scale static column mesocosms to study the physical, chemical, and microbiological changes occurring over time in this CT beneath MFT deposition. The results were compared to those in the control systems. The study showed that over one year of incubation, the release water composition had been altered by reduction in the concentrations of calcium and sulphate ions, and the electrical conductivity; the MFT had a steady densification rate; and the CT had a densification rate comparable to the control system. The author concluded that the CT beneath MFT deposition may be a beneficial disposal scheme for oil sands tailings management.

Pros

- Improves quality of CT release water by reduction in the concentrations of calcium and sulphate ions, and the electrical conductivity.
- Improve CT and MFT densification rates.

Cons

- Effects are modest.

Knowledge gaps

- Further research is necessary in a controlled laboratory experiment to better understand the physical, chemical, and microbiological processes. This will help to assess the viability of implementing full-scale field testing.

Stage of technology

- Basic research.

3.2.12 Increase Tailings Sand Density

This technique aims to reduce segregation by increasing solids content of tailings sand slurries in the pipeline prior to beaching.

Pros

- High solids content slurry can be stacked at a significant slope and will promote dewatering by gravity drainage.

- The internal surcharge of coarse solids will accelerate the rate of dewatering of the contained fines.
- Formation of a partially segregating system.

Cons

- Difficulty in raising the solids content of a mix high enough to give a product which will stand on a slope, by blending existing slurries.
- Difficulty in pumping high solids content material.
- Surcharging (internal) does not significantly accelerate the rate of dewatering unless flocculants are added.
- Addition of solids, such as sand, only raises the solids content, not the viscosity (segregation is not eliminated).
- Equipment access may be an issue due to cyclic mobility (liquefaction) during trafficking.

Knowledge gaps

- Effective way of increasing tailings sand density has not been found.

Stage of technology

- Basic research.

3.3 Natural Processes

Natural processes involve using environmental or geophysical processes to remove water from solids.

3.3.1 *Sedimentation/Self-weight Consolidation*

Sedimentation and consolidation are natural dewatering processes that use the force of gravity to separate the suspended solids from the tailings stream. Two states of sedimentation/consolidation are distinguished in the settling of suspended solids. The first state, called hindered settling, is characterized by the absence of interparticle forces below the critical density and a reduced settling rate is caused by the increasing hydraulic resistance during further dewatering of the pore volume. In this case the whole weight of the sediment is compensated by the buoyancy and the pore water pressure above the hydrostatic level. The second state is called consolidation and is defined by formation of a sediment network structure above the critical density which is able to carry a part of its own weight. MFT settlement is also resisted by repulsive forces between particles.

This technology has been used for 40 years in oil sands, but despite tens of millions of dollars of research, understanding of the fundamentals of densification of high-fines fluid tailings remain elusive.

Pros

- Tailings are pumped directly to a disposal area and are allowed to passively dewater while supernatant is decanted and recycled back into the process.

- Low cost, elimination of mechanical dewatering equipment necessitated by an accelerated process approach.
- Maintenance requirements and operator expertise are minimal as the approach is basic with limited technology.
- Robust in that it is effective for widely varying feed characteristics.

Cons

- Requires vast areas to provide sufficient storage.
- Engineered dams may be required, with the associated construction and maintenance costs.
- Pumping logistics are to be considered with the generally increased distance.
- Chemical treatment may be necessary to enhance rate of settlement.
- Relatively slow process which results in only partial dewatering.

Knowledge gaps

- Need to better understand the interparticle forces inhibiting MFT to dewater to higher solids content.
- Sedimentation and consolidation analysis is of great practical importance in slurry handling processes. Sedimentation and consolidation phenomena are conventionally treated as two separate processes although in practice the phenomena are interconnected and there is a need to analyze them together.
- An improved fundamental understanding of the fluid to solid transition and the concomitant strength development will lead to better design and management of tailings facilities. Both sedimentation and consolidation phenomena are reciprocally recognized but a unified theoretical formulation that can correctly capture a transformation from sedimentation to consolidation does not exist yet and current practice is often based on empiricism.

Stage of technology

- Mature (operates commercially).

3.3.2 *Evaporation/Drying*

This technology consists of depositing CT or MFT in thin lifts and allowing the lifts to desiccate (remove moisture) by evaporative drying. Promotion of natural drying is often considered the most cost-effective means of dewatering fine-grained material.

The potential for evaporation/drying as a technology is limited by the climate of Northern Alberta. Mean annual precipitation (rain and snow) in Fort McMurray from 1971 to 2000 was measured as 455 mm (Environment Canada 2010), of which, 363 mm were measured between April 1 and October 31 (months with average daily temperature above 0°C). Yearly evaporation from lakes has been estimated at 578 mm (Abraham 1999) leading to a deficit of 215 mm. Although the oil sands exists in a water deficit

(evaporation exceeds precipitation), evaporation rates are typically less than the rate of release water from the tailings.

To achieve maximum evaporation, excess surface water from precipitation or consolidation must be adequately drained from the surface of drying tailings. If adequate drainage is not provided, desiccation of the tailings will not occur until the evaporation rate exceeds the rate of water release from consolidation and precipitation. Assuming all precipitation is drained away from the surface of a tailings deposit, the potential evaporation is limited to about 3 mm/day.

Material properties such as particle size distribution, saturated/unsaturated hydraulic conductivity and soil-water characteristic curve influence the availability and flow of water to the evaporation surface. In fine tailings where bitumen content is relatively high, the bitumen may form a surface coating that thickens as the tailings dewater. This layer may impede moisture transfer from the tailings to the atmosphere essentially reducing or halting evaporation. The presence of salts within the fine tailings leading to salt crusting may also lead to a reduction in the evaporation rate. This may be due to an increase in the tailings surface albedo, resistance to moisture transfer at the surface and decrease in the saturation vapor pressure (Newson and Fahey 2003).

Suncor (2009) has conducted several small-scale and large-scale pilot tests to evaluate methods to undertake MFT drying. Suncor investigated different chemical additives such as hydrated lime/gypsum and polymers. They indicated that the use of polymers decreased the drying time, increased the allowable lift thickness (19 cm lifts), and improved the strength and the release of free water from the MFT mixture. In 2009, Suncor applied for regulatory approval for Tailings Reduction Operations (TRO) Experimental Facilities to test MFT drying on a prototype scale. On the basis of successful testing of MFT drying, Suncor (2009) indicated that it has a sufficient level of confidence in the process to incorporate MFT drying into its business plan, pending regulatory approval¹. Continued testing is focused on optimizing performance in the field, rather than fundamental research.

It seems likely that drying or freeze-thaw will be an important component of future oil sands fine tailings management, despite the large areas required and the vagaries of the weather.

Pros

- Resulting surface is trafficable with modest equipment and suitable for additional layers for dewatering or sand capping and terrestrial reclamation.
- Post-reclamation settlement is expected to be small.
- Development of natural cracks as shrinkage occurs provides drainage channels for horizontal movement of water and additional surface area for evaporation.
- Tailings may be amended with chemical additives (polymers) to enhance dewatering and increase slope angles.

¹ Suncor received ERCB approval for their Tailings Reduction Operations in June 2010.

Cons

- Requires surface water management.
- Only thin layers can be treated and repeated through the summer.
- Large areas are required to treat large quantities.
- Need dyke structures (cell construction).
- Salt crusting or bitumen on the surface may reduce the evaporation rate.
- Vagaries of the weather can make this technology challenging to manage.
- Requires near-level sites to minimize earthwork.
- Labour intensive.
- High operational costs.
- Trafficability of final deposit is still only modest.

Knowledge gaps

- Cell configuration including degree of slope, length and width.
- Cell management including MFT distribution, application rate, lift thickness, mechanical compaction, and release water control.
- Storage and preparation of polymer, including concentration and mixing with MFT.
- Effect of varying MFT constituents and/or solids.
- Evaporation from cracked media,

Stage of technology

- Applied research and demonstration.

3.3.3 Accelerated Dewatering (*rim ditching*)

This technology involves the deposition of a large volume of MFT in a dedicated cell and the subsequent use of evaporation and rim ditching to accelerate dewatering to create a final deposit of suitable density to support dry landscape reclamation. The process relies on the evaporation rate from the MFT deposit exceeding the rate of water release, thereby allowing a crust to form on top of the deposit (Lahaie 2008). This crust in turn allows a ditching network to be established that promotes further dewatering and crust thickening as the ditch is worked toward the bottom of the deposit. This technique lowers the water table of the deposit accelerating the dewatering process. Low pressure vehicles pulling ploughs can be used to increase the exposed surface area and promote surface drainage by creating shallow ditches and encourages desiccation by evaporation. Use of chemical amendments such as lime or gypsum to promote dewatering is a common feature of this application (Fair 2008).

This technology has been employed successfully by the Florida phosphate industry for the densification of large volumes of suspended fine clay particles. The key of clay pond

reclamation is the formation of cracks to enhance evaporation (Carrier 1997, 2001). Cracks form from the face of the ditch into the interior of the pond so that even distant surface water can drain through the cracks into the ditch.

Synchrude started studying this technology by conducting bin tests at CANMET (Fair 2008) and then developing a 60,000 m³ field pilot test that started in 2009. The field pilot test will be operated for several years, with the objective of providing planning and geotechnical parameters and to act as a basis on which environmental assessments can be carried out over the complete development cycle – pond filling through to reclamation.

Pros

- Proven technology in Florida with phosphate tailings.
- Little intervention and low operational costs.
- Stand-alone deposit.
- Potential MFT volume reduction of 50% after three to five years.
- Can be implemented in deep impoundments, 30 m plus (Lahaie 2008).
- Formation of cracks accelerates the dewatering process.
- Resulting soft material can be suitably capped and reclaimed.

Cons

- Unproven in Alberta oil sands at commercial scale.
- Expensive chemical addition potentially needed to control bitumen fouling.
- Large up-front capital cost to build dykes.
- Requires additional disturbance footprint.
- Deepening of the rim ditches requires judgement and experience.
- Vagaries of the weather can make this technology challenging to manage.
- Labour intensive.
- Benches cut in the earth embankment are costly and time consuming.

Knowledge gaps

- Need to engineer the operational method to implement it at large/commercial scale.
- Optimization of impoundment thickness.
- Research should be directed at accelerating the formation of the cracks in the MFT.
- Improved understanding of drainage and evaporation processes, especially in cracked media.

Stage of technology

- Applied research and demonstration, mature elsewhere.

3.3.4 *Freeze/Thaw*

This technology consists of depositing CT or MFT in multiple thin layers which are allowed to freeze and then the frozen mass is allowed to thaw the following summer. The freezing cycles causes consolidated soil-like “peds” to form, developing a fissured structure throughout the deposit which quickly drains when thawed. A considerable amount of water is released when thin layers (5 cm to 15 cm) of MFT are subjected to freeze-thaw cycles (Dawson and Sego 1993, Johnson et al. 1993, Proskin 1998).

Laboratory investigation (Proskin 1998) demonstrated that the freeze-thaw process overconsolidates the MFT as the freezing front advances downward in the deposit. Suctions are created within the solids when water flows to the vertical and horizontal ice lenses which form a three dimensional reticulate ice network surrounding peds of overconsolidated MFT. During thaw the remnant fissures developed by the ice provide channels for fluid flow. The microfabric of particles was observed to change from an edge to face flocculated, disaggregated card-house fabric to a compact, aggregated structure. The latter microfabric retains less water which accounts for the significant increase in solids content from 35% to 56% (Beier et al. 2009). The altered fabric reduces the MFT compressibility and increases its hydraulic conductivity as much as 100 fold at low void ratio (Proskin 1998).

A significant thickness of material can be treated by freeze/thaw if the freezing process is repeated on top of a previously frozen layer. The limit of how much MFT can be treated per year is probably related to how much can be thawed the following summer, as calculations indicate that more MFT can be frozen in a Fort McMurray winter than can be thawed in the summer (Beier et al. 2009).

The effect of freeze-thaw dewatering can be enhanced via chemical amendment and altering drainage conditions. Sego (1992) investigated the effect of chemical amendment of the MFT by adding sulfuric acid (H_2SO_4) and replacing monovalent sodium cations with divalent calcium cations (from quicklime CaO) prior to freezing. He found that chemical amendment causes an additional 18% increase in solids content associated with freeze-thaw.

Suncor is currently evaluating the freeze-thaw technology concurrently with the MFT drying technology.

Pros

- Low upfront capital cost.
- Significant thickness can be treated by freezing subsequent layers on top of a previously frozen layer.
- Results in moderately low strength deposits up to 14 kPa in one year (Dawson and Sego 1993, Proskin 1998) with low settlements. This may open up other reclamation options. Suitable for hydraulic sand capping as well.

Cons

- Thickness is related to how much can be thawed the following year (2 to 3 m).
- Resulting material remains saturated and soft so is only suitable for hydraulic sand capping or reclamation using specialized equipment.
- Requires large areas and containment structures because of the thin fluid lifts.
- Managing the pumping of fluids during extremely cold temperatures is challenging.
- Labour intensive.
- Success subject to weather and operator diligence.

Knowledge gaps

- Optimum lift thickness.
- Understanding the likely final solids content/consistency in large scale applications to develop effective reclamation strategies.
- Development of a robust operational system.

Stage of technology

- Applied research and demonstration.

3.3.5 *Plant (Evapotranspiration) Dewatering*

Suitable plant species growing in high water content tailings can dewater the tailings by transpiration through the leaves and associated root systems (Johnson et al. 1993, Silva 1999). Plants can transpire large quantities of water during the growing season; the rate of water loss may exceed that of free water evaporation and continue long after the surface has become dry.

Research conducted by Silva (1999) shows that suitable plant species growing in CT have the ability to remove the water through evapotranspiration increasing the matric suction in the deposit. This results in an increase in the undrained shear strength and bearing capacity within the root zone. Furthermore, the plant root system provides fibre reinforcement, which should also contribute to the increased bearing capacity of the rooted tailings. Plants can also draw water from depths that may be greater than that achievable by other methods. However, highly saline and sodic tailings can limit the establishment of vegetation.

Pros

- Suitable plant species can grow in tailings removing water by transpiration through the leaves.
- Plants transpire large quantities of water during the growing season.
- Absorption of CO₂ by plant.

- Root development increases bearing capacity at the tailings surface facilitating access of low pressure equipment for reclamation.
- Vegetation can assimilate minerals and various organic toxic compounds and much of this material can be removed by timely harvest.

Cons

- High salinity of tailings can inhibit establishment and healthy growth.
- Challenges getting seeds to develop in the deposit – work best with seedlings.
- Placement of fertilizer, seedlings/seeds and other amendments onto large deposits is not well developed.
- Depth of dewatering is limited by root depth.
- Concern regarding use of non-native and potentially invasive species.

Knowledge gaps

- Conduct small-scale pilot tests to assess viability of this technology using native species.
- Develop methods to place seedlings, fertilizer and other amendments onto the deposit.
- Evaluate possibility of using in thin lifts similar to evaporation/drying. Buried vegetation will decay adding organic matter to the tailings.
- Evaluate performance in conjunction with freeze-thaw technology.

Stage of technology

- Basic research. Previous applied research and development were conducted in the field (Johnson et al. 1993).

3.4 Chemical/Biological Amendment

Chemical/biological amendments involve changing the properties of the tailings to remove water.

3.4.1 *Thickening Process*

Thickened Tailings (TT) technology, also known as paste technology, involves rapid settling and sedimentation of suspended fines within a process vessel called a thickener through the addition of chemicals that aid in flocculating the fines solids and producing water that is suitable for reuse back to the extraction process with little loss of process water temperature. This means less make-up heating is required resulting in lower imported energy costs and reduced greenhouse gas emissions. Additionally, the accelerated settling rate of the fines produces a concentrated stream of fine solids which can be deposited with less land disturbance and offer the potential for accelerated land reclamation.

Thickeners also have a rake mechanism that transports bed material to the underflow, assists dewatering of the bed material and scrapes away deposits from the base. Normal

thickener processing yields a density of about 30% solids content. Higher solids content are reported but may be due to the addition of sand. The typical residence time in a thickener to increase the solids content of suspended fines to 30% is half an hour (Devenny 2009) whereas it takes a few years to achieve the same solids content through gravity settlement of TFT in a tailings pond. Super flocculating agents may achieve higher densities but are approached with caution in case the presence of the super floc in return water adversely affects extraction (Devenny 2010).

TT technology is an integrated engineering system. It generally includes the thickener feed preparation process, thickener type selection and thickening process, flocculant selection and flocculation technology development, tailings transportation, tailings deposition and consolidation, strategy of reuse of thickener overflow water, and impacts on environment and existing plant operation. The choice to commercially implement TT technology to manage fine tailings is ultimately dependent upon the ability to achieve the necessary tailings deposition requirements using a thickening process that is suitable to the oil sands extraction process. It must also be cost competitive relative to other tailings management options (Yuan and Lahaie 2009).

Syncrude has conducted several large-scale thickened tailings evaluations (Fair 2008). The most recent field pilot utilized a High Compression Thickener Pilot. Syncrude views this technology as commercially viable and it is being considered for implementation at Syncrude's Aurora North and South mine sites. Shell Muskeg River thickens a fine tailings stream, but only to modest densities.

Pros

- Targets new fines.
- Quickly recovers process water with its contained heat.
- Densifies the tailings outlet stream enhancing fines capture in sand deposits. The fines captured will not be available to make more MFT.
- Resulting material can be deposited with less land disturbance with the potential of accelerated land reclamation.
- Reduces groundwater concerns.
- Requires more modest containment.
- More stable deposits.
- High solids underflow from thickener.

Cons

- Resulting material is still a slurry, requiring further treatment.
- Requires careful operational control and qualified operations staff.
- Does not address legacy MFT.
- Bitumen accumulation in the thickener feedwell can impair flocculation efficiency.

- High startup and operational costs, experienced operators needed.
- Long-term consolidation settlement.
- Adverse impacts of plant upset conditions.
- Tailings can only be stacked at slopes of 0.5% to 1%.

Knowledge gaps

- Thickener feed preparation process, thickener type selection and thickening process.
- Flocculant selection and flocculation technology development.
- Contribution of raking mechanism to rate of dewatering.
- Thickened tailings transport (conveyor and positive displacement pump), deposition and consolidation.
- Reuse of thickener overflow water.
- Impacts on environment and existing plant operation.

Stage of technology

- Applied research and demonstration, mature elsewhere.

3.4.2 *In-Line Thickened Tailings (ILTT) Technology*

This technology consists of injecting and mixing flocculants and coagulants into the high fines content cyclone overflow tailings (COT) in an in-line multi stage fashion. Conceptually by binding fine particles at low solids content into flocs, the hydraulic conductivity is increased, tortuosity is decreased and the mass of the failing flocs is increased. This process is aimed to improve settling, consolidation, and strength behaviour of COT (Jeeravipoolvarn et al. 2008a).

Suncor started a field pilot project in late 2005 to demonstrate the pilot scale behaviour of tailings produced from the ILTT process (Jeeravipoolvarn et al. 2008a). The project included two ILTT pilot ponds. Geotechnical field investigations including pore pressure measurements, solids and fines content measurements and vane shear strength measurements were performed to monitor the compression behaviour of the deposits. Preliminary findings indicate that this process produces fine tailings that undergo rapid hindered sedimentation from solids contents of about 4% to 30% within days followed by consolidation and segregation phenomena at higher solids contents. Production of CT using ILTT instead of MFT was also examined at a sand to fines ratio of 4:1 and it was found that ILTT-CT is far superior to MFT-CT in both hydraulic conductivity and undrained shear strength (Jeeravipoolvarn 2010). Shearing due to tailings transportation was investigated and it was found that the sheared ILTT's hydraulic conductivity and undrained shear strength are lower than that of nonsheared ILTT however the properties of the sheared ILTT are still significantly better than that of MFT.

Suncor uses in-line thickening as part of its TRO project.

Pros

- Rapid dewatering of COT.
- Require a relatively small containment area to store ILTT.
- Undrained shear strength of ILTT is considerably higher than that of COT or MFT. The combination of the high hydraulic conductivity and the high undrained shear strength opens up other possible dewatering techniques.
- Reduce energy cost by returning water with its heat.
- No or little coagulant addition will be required to make CT from ILTT resulting in a reduction in cost and an increase in the quality of the recycle water.
- Reduction of new MFT formation and storage.

Cons

- Floc disruption during tailings transportation can reduce ILTT's high hydraulic conductivity and undrained shear strength.
- The advantage of being more permeable of ILTT can disappear at higher solids contents.
- Challenging to pump ILTT from depositional ponds and mix it with cyclone underflow tailings to make CT without a significant breakdown of the floc structure.
- Potential adverse impacts on water quality due to the addition of coagulants and flocculants.
- Requires increased operational control.
- High operational cost.

Knowledge gaps

- Further research is required to confirm the influence of shearing on segregation behaviour of CT made from ILTT under a dynamic condition.
- Viability at large-scale.
- Robustness of the technology with tailings variability.
- Quality of released water from the process.
- Shear thinning and methods to reduce its effects.
- Methods to treating MFT directly without dilution.

Stage of technology

- Applied research and demonstration.

3.4.3 Whole Tailings Coagulation

In this technology, a coagulant is added into the tailings pipeline to generate whole-tailings CT or partially segregating CT. Coagulants cause aggregation of colloids by changing their characteristics or surface charge.

Due to its gap-graded nature and low initial solids content, the coarse particles ($>44\ \mu\text{m}$) in the tailings stream segregate from the whole tailings and the stream of fines particles flow into a pond and form a fluid deposit (TFT). To prevent segregation, it is necessary to modify the tailings stream by increasing the solids content, increasing the fines content, or changing the apparent size of the fines (FTFC 1995). Coagulating or aggregating the fines with chemical agents, such as lime, sulphuric acid, gypsum, flyash and their combinations, can change the tailings stream into a nonsegregating slurry.

Coagulation is the process in which destabilization is achieved by the addition of salts which collapse the double layer so reduce, neutralize or invert the electrical repulsion between particles. The most common coagulants are mineral salts: aluminum sulfate, ferric chloride, lime, calcium chloride, magnesium chloride.

This technology is not very robust for operating oil sands plants, but led to the development of CT technology using cycloned sand to increase the density of the slurry and reduce the potential for segregation.

Pros

- Resulting material may be suitable for vacuum or pressure filtration (not an economical method) or building beaches and slopes (less than 1% slope to minimize segregation).
- Recovers large amounts of process water and reduces water capture in MFT.
- Sedimentation and initial consolidation commence almost immediately after deposition and is complete within a short period of several days to a few weeks.
- Captures new fines reducing MFT generation.

Cons

- Chemical reagents probably generate detrimental effects on recycle water quality.
- High operational cost.
- May need to be used with flocculants.
- Potential adverse impacts on water quality due to the addition of coagulants and flocculants.

Knowledge gaps

- Understand the coagulation characteristics of whole tailings.
- A rheology modification chemical is required to facilitate the fines material integrating in the coarse structure.

Stage of technology

- Applied research and demonstration.

3.4.4 Whole Tailings Flocculation

In this technology, a flocculant is added into the tailings pipeline to generate whole-tailings CT or partially segregating CT. Flocculants cause chemical bonding of colloids. Flocculation is a technique in which discrete, colloidal-sized particles are agglomerated by an appropriate reagent and, as a result, settle out of suspension.

Flocculation is used to describe the action of polymeric materials which form bridges between individual particles. Bridging occurs when segments of a polymer chain adsorb different particles thus help particles aggregate (Suncor 2009). Flocculants carry active groups with a charge which will counterbalance the charge of the particles. Flocculants adsorb particles and cause destabilization either by bridging or charge neutralization. In flocculation, individual particles are united into rather loosely-bound agglomerates, called *flocs*. Generally, flocs produced by polymers are much stronger than those formed by coagulation; the particles are held together with elastic bonds, not merely by weak Van der Waals forces.

Three groups of flocculants are currently available: mineral (silica, bentonite, alum, ferric hydroxide); natural (starch derivatives); and synthetic (polyacrylamides).

Shear thinning, especially due to the large volumes of sand in the slurry interacting with the flocculant is a concern.

Pros

- Resulting material is suitable for vacuum or pressure filtration (not an economical method) or building beaches and slopes (less than 1% slope to minimize segregation).
- Recovers large amount of process water.
- Sedimentation and initial consolidation commence almost immediately after deposition and is complete within a short period of several days to a few weeks.
- Hundreds of commercial flocculating reagents are available.
- Addresses new fines.

Cons

- Unpredictable performance due to tailings variability.
- Requires enhanced operational control/care.
- Use of chemical reagents may generate possible detrimental effects on recycle water quality.
- High operational cost.
- May need to be used with coagulants.

Knowledge gaps

- Understanding the flocculation characteristics of whole tailings.
- Impact of bitumen and sand on flocculation process.
- Quality of released water from the process.
- Evaluation of flocculants should include clay mineralogy, age of the slurry, the method of flocculant introduction, the dilution of the slurry, the pH of the slurry, the mixing shear and the conditioning and contact time.
- A rheology modification chemical is required to facilitate the fines material integrating in the coarse structure.

Stage of technology

- Applied research and demonstration.

3.4.5 *In-Situ Biological Treatment*

In this technology, inoculation or enhancement of bacterial action are used to densify MFT or fine tailings. Results of a laboratory investigation (Fedorak et al. 2003) conducted on MFT and CT samples from three oil sands companies suggested that methane formation may increase the rate of tailings densification. Biological methane production (methanogenesis), is accomplished by a consortium of anaerobic microbes and can accelerate densification of MFT by generating channels in the tailings where gas bubbles rise (Guo 2009). These channels can then allow drainage of water due to excess pore pressures within the tailings mass. The generation of methane from oil sands tailings ponds is an environmental concern, in part because methane is a potent greenhouse gas (however cannot likely be controlled). This phenomenon may also benefit tailings management in the oil sands by hastening the consolidation process.

Pros

- Low cost.
- Micro-biological activity produces carbon dioxide and methane leading to formation of gas pockets which coalesce to provide vertical drainage channels accelerating drainage and densification.

Cons

- Limited knowledge.
- This process is difficult to control in a large scale.
- Not proven technology.
- Lack of understanding of microbes present in MFT.

Knowledge gaps

- Need to understand the gas migration process through MFT and how it relates to consolidation of MFT. Also consolidation that may shut off the drainage channels has to be further studied.

- Better understanding of microbes present in MFT produced by different oil sands extraction operators.
- Need to identify roles that these microorganisms play in methanogenesis and MFT densification in the tailings ponds.
- Need to better quantify impact in MFT densification and its effectiveness in the long term.

Stage of technology

- Basic research.

3.4.6 *In-Situ Chemical Treatment*

This technology consists of injecting and mixing chemical reagents into MFT in situ. Chemical additives injected in tailings ponds can increase the efficiency of the consolidation process by changing the pH or by promoting coagulation and/or flocculation. An increase or decrease in pH can reduce the surface activity of the clay-organic materials and collapse the MFT card-house structure (Chalaturnyk et al. 2002). This structure collapses as the pH increases above 10 (increase in OH^- ion concentration), or the pH decreases below 6 (increase in H^+ ion concentration).

Pros

- Chemical reagents can reverse the dispersive effects of caustic used in the extraction process.
- Address legacy MFT.
- Does not require additional footprint because the tailings are treated in situ.

Cons

- Limited knowledge on coagulants and flocculants.
- Not proven technology.
- Injecting and mixing in situ can be very challenging.

Knowledge gaps

- Develop a systematic method to ensure adequate mixing.
- Understand required dosages and associated costs.
- Determine net potential impact/benefit.
- Need to identify roles of different chemical additives in modifying tailings properties.

Stage of technology

- Basic research.

3.4.7 *Reduce Dispersion of Fines in Process*

This technology consists of changing the tailings water chemistry to reduce the amount of fines dispersion and trap more fines within the tailings sand.

High temperature and the caustic dispersing agent (NaOH) have formed the basis of the CHWE process used successfully on a commercial scale to recover bitumen from oil sands ore. However, the CHWE process results in the creation of extremely dispersed, high-void-ratio fine tailings composed primarily of silt, clay, water, and residual bitumen. These caustic-based fine tailings exhibit extremely low consolidation rates and undrained shear strengths and require considerable land for storage. Processes different from the established CHWE process have been developed to work at a range of temperatures or without the use of sodium hydroxide (Kasperski 2001). One such process is the “other six lease owners” (OSLO, the consortium of companies that piloted the process) hot water extraction process (Miller et al. 2009, Sury et al. 1993), a non-caustic bitumen extraction technique developed to improve bitumen recovery and produce tailings with reduced fines dispersion, in the hope of improved consolidation and strength properties of the fine tailings.

The OSLO Cold Water Extraction (OCWE) technology is part of Syncrude’s Low Energy Extraction (LEE) Process. Improved consolidation and dewatering characteristics of the LEE tailings are attributed to limited clay dispersion because of the low pH operating condition.

Pros

- Dispersion is reduced by eliminating the use of sodium hydroxide in the extraction process.
- Improves the energy efficiency, reducing operational costs.
- Reduces the volume of process water.
- Brings significant environmental benefits.
- Produces a tailings effluent with better short-term consolidation properties.
- Allows hydraulic sand capping soon after deposition and can subsequently be reclaimed to support terrestrial land uses.

Cons

- Contradicts the existing knowledge of bitumen extraction.
- Lower bitumen extraction efficiency.
- Does not appear to enhance long-term consolidation rates.
- Total volume of soft material increased substantially.

Knowledge gaps

- Evaluate segregation behaviour.
- Test additional additives to increase bitumen extraction efficiency.

- Evaluate sedimentation, consolidation and strength performance characteristics.

Stage of technology

- Commercial demonstration and mature.

3.5 Mixtures/Co-disposal

Mixtures/co-disposal technologies involve mixing tailings streams with a variety of available soil materials and waste products to increase tailings density.

3.5.1 *Composite/Consolidated Tailings (CT)*

The CT process was developed at the University of Alberta (Caughill et al. 1993). CT technology involves mixing densified extraction tailings (coarse sand from cyclone underflow tailings, CUT) and MFT with an amendment (typically gypsum) to create a non-segregating slurry, with subsequent discharge into a tailings pond to form a rapidly consolidating, soft, cappable deposit capable of meeting various land uses and landscape performance goals. The CT process is designed to run at an average of 20% fines (4:1 sand to fines ratio) to produce a slurry density of approximately 60% solids.

Suncor was the first, in 1995, to apply the CT process on a commercial basis in its Pond 5 and has continued to apply the technology (Suncor 2009). Syncrude conducted a non-segregating tailings field demonstration in 1995, followed by the CT prototype in 1997-1998. A commercial CT plant has been in operation at the Syncrude Mildred Lake site since 2000.

Despite many years of commercial use that has produced tens of millions cubic metres of CT, the process is still under review. Apparently operators have experienced difficulty in consistently making on-spec CT.

CT remains the primary tailings management technique for existing and future plans for several operators and efforts are underway to assess and improve deposit performance.

Pros

- Relatively low cost.
- Operationally implemented at large scale.
- Deals with legacy MFT.
- Non-segregating tailings slurry.
- Consolidates over a short time to form a solid landscape suitable for hydraulic sand capping and terrestrial reclamation.
- Tailings management flexibility.
- Consolidation rates for on-spec CT higher than expected.

Cons

- Requires robust system to deal with variability of feed.

- Requires large containment until it solidifies (containment is expensive).
- Low energy efficiency.
- Operators have experienced difficulty in consistently depositing on-spec CT. Off-spec CT has consolidation properties similar to those of MFT.
- Careful engineering and operation is required to prevent segregation during deposition.
- Requires large amount of sand, supplemental source of sand will be needed to treat the legacy MFT.
- Dosage of gypsum is quite large resulting in the buildup of calcium and sulphate ions in the recycle water which in time will negatively affect bitumen extraction.
- Produces additional MFT from the cyclone overflow.
- Potentially causes H₂S emissions by anaerobic reduction of SO₄⁻² with the residual bitumen in the tailings.
- Bulking up of material with poor consolidation characteristics.

Knowledge gaps

- Develop a robust operational system to make on-spec CT.
- Evaluate new amendments (alternative to gypsum) such as CO₂ (Canadian Natural Resources Limited 2009), alum and polymers.
- Methods to improve off-spec CT performance.

Stage of technology

- Mature (operates commercially).

3.5.2 *MFT Spiked Tailings*

This technique consists of injecting MFT into a fresh tailings stream to form a segregating slurry with a high fines content. The concept is that a high proportion of fines can be captured in the beach formation following hydraulic discharge. The fines can be trapped in the void spaces between the sands grains leading to an overall reduction in fluid fine tailings. This concept has the merits of simplicity and low cost. However, testing has not demonstrated an important recapture process.

This technique is very limited in its scope as a means of dewatering fines trapped in the voids and also as a means of reducing MFT formation. It remains a potential option for small increases in beach fines capture. The resulting trafficability of spiked beaches is marginal.

Pros

- Address legacy MFT.
- Practical and cost effective.

Cons

- Trafficability of spiked beaches is marginal.
- Additional fines in the deposits would also affect their rate of consolidation and this could influence the rate at which each lift could be built, as well as the ultimate height achievable safely.

Knowledge gaps

- Methods to increase fines capture without compromising trafficability.
- A better understanding of the role of fines from MFT versus the fines from whole tailings and the impact on spiked tailings geotechnical performance.

Stage of technology

- Applied research.

3.5.3 *Mixing MFT with Clearwater Overburden*

This technology consists of mixing MFT with Clearwater clay (Kc) to form a semi-solid mixture suitable for storage in polders. The Clearwater formation clay is very dry and has a considerable affinity for water. The Clearwater formation was deposited on top of the McMurray formation and contains marine deposits that formed in the deepened sea. Some layers of the Clearwater are sandy but most are clay-shale that contains a considerable amount of bentonite. Some geotechnical properties of Kc at the Syncrude site were reported by Lord and Isaac (1989): clay content ranges from 11% to 40%, liquid limit ranges from 37% to 53% (medium to high plasticity), moisture content ranges from 16% to 25% (low moisture content).

The natural matric suction of the clay will remove water from the MFT solving two problems simultaneously: reducing costs of overburden transport to the disposal dump (hydraulic transport would be a much cheaper transport method than trucking) and dewatering MFT for disposal. The clay will continue extracting water until the moisture content of the two materials reaches a state of equilibrium.

This technique was successfully demonstrated by Syncrude (Dusseault et al. 1987). Scale up remains an issue, and the total amount of soft material is increased with this methodology.

Pros

- Clearwater formation contains a considerable amount of bentonite that can be blended with MFT to extract large amounts of water from the MFT.
- Kc is abundant in overburden in the mineable oil sands area.
- Avoids the use of costly chemicals and mechanical dewatering machines.
- Process can be applied to any thickness (compared to technologies that rely on natural processes).
- Resulting material deemed adequate for stacking.

- High strength and rapid stabilization allows early access onto the deposit for reclamation.

Cons

- Controlling the deposition strategy to optimize the blending of the coarse and fine waste feeds is challenging.
- It is only really economic where the two feeds can be pumped together or blended for in-pit storage.
- The resulting mix would not be pumpable.

Knowledge gaps

- Quantification of mixing proportions depending on the material properties and how to obtain adequate mixing.
- Evaluate methods of transportation of the resulting mix.

Stage of technology

- Applied research, but discontinued.

3.5.4 *Mixing MFT with Other Overburden*

This technology consists of mixing MFT with glacial materials (tills, clays, sands) to form a semi-solid mixture suitable for storage in polders. This technique is similar to the previous one but the glacial materials have a lower water absorption capacity.

Canadian Natural Resources Limited (2009) is conducting a geotechnical feasibility study of MFT desiccation and mixing with overburden on the west slope of Pond 1. Syncrude (2008) categorized this technology as a 'minor or less capable' technology and it was not considered as playing a primary role in the fine tailings solution (for the Mildred Lake site).

Pros

- More abundant overburden material to mix with MFT.
- Similar to the technology in Section 3.5.3 but the glacial materials doesn't contain bentonite.

Cons

- Same as the technology in Section 3.5.3 plus less capacity to uptake water from MFT than Kc.

Knowledge gaps

- Quantification of mixing proportions depending on the material properties and how to obtain adequate mixing.
- Evaluate methods of transportation of the resulting mix.

Stage of technology

- Basic research and Applied research.

3.5.5 *Mixing MFT with Reclamation Material*

This technology consists of mixing MFT or CT with peat moss to form a semi-solid mixture suitable for early reclamation. For consolidated CT deposits, rototilling is used for mixing, and is expensive.

Li and Fung (1998) conducted greenhouse and field experiments mixing peat moss with MFT, CT and tailings sands. They concluded that it is possible to create a plant growth medium using these by-products. However, they observed that the presence of salts in the materials was the limiting factor for plant growth.

Pros

- Address legacy MFT.
- Surface material will be ready for reclamation.
- Reduces need for secondary reclamation material.

Cons

- Toxic compounds in MFT may inhibit plant growth.
- Not proven technology.
- Limited availability of reclamation material.
- Expensive and likely unable to produce commercial forest.

Knowledge gaps

- Quantification of mixing proportions depending on the material properties.

Stage of technology

- Basic research, but discontinued.

3.5.6 *Mixing MFT/CT with Coke*

This technology consists of mixing MFT/CT with coke from the bitumen refining process. Although some of the coke is used as fuel in the processing plants, the remainder is stored for use as a future energy source.

Suncor (2009) conducted a study adding coke into the CT stream to evaluate the consolidation behaviour of the mix. Syncrude (2008) categorized mixing MFT with coke as a “minor or less capable” technology.

Pros

- The mix may improve consolidation.

Cons

- Toxic compounds (nickel, vanadium and molybdenum) in coke may bioaccumulate in plants inhibiting their growth.
- Coke, a source of energy, can be lost in a deposit or difficult to obtain if later required.

- Benefits are unclear.

Knowledge gaps

- Quantification of mixing proportions depending on the material properties.
- Understanding consolidation behaviour.
- Understanding depositional behaviour (i.e., segregation).
- Assessment of toxicity in different plant species.

Stage of technology

- Basic research.

3.5.7 *Mixing Thickened Tailings with Sand*

This process involves mixing tailings sand with thickened tailings to form a non-segregating mix suitable for poldering. The deposit would be further dewatered via evaporation and then capped with a layer of overburden and seeded. This technology may be regarded as a promising technique for use in some areas but it is not yet a proven one for use in the oil sands. The application of this technology is dependent upon the demonstration of the thickened tailings technology. The results to-date indicate that thickened tailings is not a technology that has a stand-alone potential within the Syncrude tailings technology portfolio (Syncrude 2008).

In 2007, Shell began various field programs at their tailings testing facility (Shell 2009 a,b). One of the tests included mixing thickener underflow with coarse tailings to produce a non-segregating mix with high sand content (the mix is known as non-segregating tailings or NST). Shell is testing the NST process to support the objective of reduced fluid fine tailings inventory accumulation and more rapid reclamation of mined areas to terrestrial land uses.

Laboratory test results on CT made from ILLT (which has a similar concept to this technology) indicate that mixing sands with thickened tailings can produce high undrained shear strength and high hydraulic conductivity nonsegregating tailings (Jeeravipoolvarn 2010).

Pros

- The mixture has a high solids content and it may be stacked at a significant slope.
- Address new fines.
- May not require containment.
- The high fines/high solids mix will have a high viscosity which will result in formation of a non-segregating system.
- The internal surcharge of sand will raise the effective stress on the clay and promote self-weight consolidation.

Cons

- Not proven technology.
- Improper application of this technique may result in the creation of reclaimed landforms of dubious environmental and economic value, particularly because of the presence of sodic clays and bituminous residues in oil sands tailings.

Knowledge gaps

- Deeper insight into the geotechnical properties of thickened tailings/sand mixes would assist full field-scale planning tests which are extremely expensive.
- Strength and consolidation behaviour of various mixtures of sand and thickened tailings are not known.
- Evaluate liquefaction potential.

Stage of technology

- Basic research and applied research.

3.6 Permanent Storage

Permanent storage technologies acknowledge the complexity and cost associated with tailings treatment and instead opts to store tailings above or belowground in their original form.

3.6.1 *MFT Water Capped Lake*

The MFT water capping concept involves placement of MFT in a mined out pit, followed by introduction of a water cap over this deposit. The water used in the cap may range from natural surface waters to that resulting from various blends of fresh and process-affected waters. The water is initially at least five metres in depth but increasing over time as MFT consolidates. The basin is designed to function as a lake which includes design for acceptable shoreline erosion and adequate littoral zone areas. The design basis for MFT water capping relies on the concept of passive bioremediation of naphthenic acids such that concentration of these compounds will be sufficiently reduced to allow for the development of a lake feature within a future closure landscape within 5 to 10 years (Clearwater Consultants 2007).

Synchrude has undertaken extensive research work on the concept of a water-capped MFT lake since the 1980's (Fair 2008). Several large scale test ponds have been monitored over the past 20 years. A commercial scale demonstration lake is currently being constructed and is referred to as the Base Mine Lake (BML), the new name for West-In-Pit (WIP). The BML project is scheduled to start in 2012 beginning with establishment of the water cap. Once the water cap has been established in 2013, a research and monitoring program on the chemical and biological performance of BML will commence.

Several early papers have described the concept, and studies have been undertaken to confirm the suitability of the MFT water capped lake (Boerger et al. 1990, 1992, Gulley and MacKinnon 1993, MacKinnon and Boerger 1991, MacKinnon et al. 1995). A key requirement noted in these papers is that there should be no mixing between the MFT and the overlying water cap. The papers explored possible mixing by the action of surface waves. The design depth of the water cap was set to prevent such mixing.

In the mid 1990's methanogenic bacteria became active in Syncrude's Mildred Lake Basin and vigorous bubbling has been ongoing since (Devenny 2010, Guo 2009). Limited research examined the bacterial activity and noted that it could affect the viability of the permanent storage scheme (Holowenko et al. 2000, Li 2008). Different bacteria are active and consume different components of the tailings (naphtha from solvent losses, sulphate used in CT treatment, and citrate (added at Shell Albion Sands to aid extraction)). The most recent publication on the end-pit-lake concept provides an update on the concept and research (Clearwater Consultants 2007). This paper quotes Syncrude's references extensively.

Pros

- Low cost.
- Reduction of concentration of chemicals through natural microbial processes.
- Self-sustaining aquatic ecosystem.
- Geologic containment for fluid tailings where stored below original ground.

Cons

- Cannot be located where the body will recharge groundwater that may ultimately contact sensitive receptors.
- Biological activity in the fluid tailings may emit considerable gas which may result in mixing fluid tailings with overlying water.
- Regulators have not yet approved permanent storage of MFT under a water cap. Instead they have advocated for a solid trafficable landscape (Houlihan and Haneef 2008).

Knowledge gaps

- Uncertainties remain regarding function and success including water quality and toxicity, sustainability and liability.
- Accurate quantification of methane release from biodegradation needs to be addressed.
- Understand how gas production impacts long term water quality.

Stage of technology

- Applied research and demonstration.

3.6.2 Pit Lake

A Pit Lake (PL), also known as an End Pit Lake (EPL), is an engineered water body located below grade in post-mining pits. A PL/EPL may contain oil sands byproduct materials and will receive surface and groundwater from surrounding reclaimed and undisturbed landscapes. PL/EPLs will be permanent features in the final reclaimed landscape, discharging water to the downstream environment (Clearwater Consultants 2007). The PL/EPL technology is similar to the MFT water capping concept; the primary distinction is one of degree in terms of the amount of tailings at the bottom of the lake.

A PL/EPL will be established in a mined-out pit. It will consist of a bottom substrate capped with water; soft tailings may be placed on top of the bottom substrate in some cases. Other process-related materials may also be stored in the pit, including lean oil sands, overburden and process-affected water (Clearwater Consultants 2007).

Proposed sources of cap water for a PL/EPL include runoff and precipitation, seepage waters, process-affected waters and water diverted from existing rivers and streams. The development and operation of a PL/EPL will be progressive. During the pre-discharge (filling) phase, some PL/EPLs will have soft tailings placed at the bottom to be covered with cap water. The soft tailings may consist of CT, MFT or TT. These tailings become denser over time and release pore water to the cap water. During the intermediate phase, the PL/EPL will stabilize, mature and start to develop a viable ecosystem. The initial discharge phase will consist of releasing the cap water to downstream aquatic environments. Finally, in the far-future, the PL/EPL will be a biologically active, self-sustaining and functional ecosystem. The pit lake technology is still not proven. The pros, cons, knowledge gaps and stage of technology are similar to the MFT water cap technology (Section 3.6.1).

3.6.3 Store MFT in underground caverns

This technology consists of injecting MFT in underground caverns or deep wells where future contact with the biosphere is unlikely. Little work has been done on this technology and it would seem to be an unlikely candidate for further work given the volumes of tailings requiring treatment.

Pros

- Prevent additional surface disturbance, less surface tailings storage.
- Tailings can be mixed on the surface with a binder to help minimize groundwater contamination.

Cons

- High costs, particularly if binders are used.
- Tailings need to be dewatered, increasing costs.
- Requires extra manpower and equipment.
- Requires suitable location and development of caverns.

Knowledge gaps

- Need to evaluate volumes to be stored, adequate locations and costs.
- Needs to evaluate suitability of this technique to be applied in the oil sands industry.

Stage of technology

- Basic research.

4 TAILINGS TECHNOLOGY ANALYSIS

4.1 Summary Tables

Summary tables (11x17" sheets) were developed to synthesize the information presented in this report. These tables are attached in Appendix 1. The first table presents a brief description of each of the 34 technologies. The second table presents a list of the most relevant pros and cons of each technology. The third table shows a summary of the knowledge gaps and proposed areas of research. The fourth table presents a graphical view of the stage of maturity of each technology. In this table, a full bar represents completion of a stage, while a partial bar represents a relative progression into another stage of maturity.

Individual summary sheets were also developed for each technology to present all relevant information related to the technology. These sheets compile all the information (relevant to the specific technology) presented in the summary tables. These summary sheets are attached in Appendix 2.

4.2 Discussion

Natural dewatering technologies are looked upon more favorably than most since they are dependent on the use of natural processes for their effectiveness, which essentially provides free energy.

Sedimentation and self-weight consolidation give only limited densification because the low stress imposed by the low buoyant weight of the fined-grained particles is insufficient to overcome the gel strength of the thixotropic oil sands fine tailings. The rate of dewatering is therefore slow and the extent of dewatering may be poor within a reasonable time-frame. Dewatering of fines by gravity processes actually appears to stop completely at approximately 30% solids content. Development of a high solids content material which could be strong enough for use as a self-supporting mine back-fill is not viable solely by self-weight consolidation of current tailings fines streams.

Evaporation/Drying and Accelerated Dewatering offer considerable promise especially when they are considered as part of a technical package. These technologies rely on solar radiation and wind action to accelerate the rate of water evaporation from soils. Accelerated dewatering uses the rim-ditching technique to enhance the evaporation of fines layers. Low pressure vehicles pulling ploughs can be used to increase the exposed surface area and promote surface drainage by creating shallow ditches and encourages desiccation by evaporation. Syncrude is currently conducting field tests to evaluate the

suitability of the Accelerated Dewatering technology. Suncor is conducting field tests of the evaporation/drying dewatering technology.

Freeze-thaw seems ideally suited to the geographical location of Fort McMurray. This technique may be useful as an adjunct to other processes, such as evaporation and accelerated dewatering. However fluid management at very cold temperatures and vagaries of the weather remain a challenge.

Dewatering using physical/mechanical processes (centrifuges, filter presses, vacuum filters, thermal drying, electrical, etc.) involves costly machinery/equipment and the results are often poor. In particular, oil sands tailings have both high fines and residual bitumen so that it is difficult without chemical reagents to effectively dewater by pressure filtration. High investment costs are necessary to obtain satisfactory results. There are also two little-considered drawbacks which are common to all mechanical dewatering processes; they produce a cake which must be transported to the disposal site and the cake must be stacked on arrival at the disposal site. The long term objective of this class of technologies is to develop stackable tailings with significant benefits for land reclamation. From this group, centrifugation and wick drains combined with surcharge loading seem to have good potential for dewatering tailings at a large commercial scale. Syncrude is currently conducting a field research demonstration using centrifuge dewatering technology. Suncor is testing the use of wick drains on one of their CT ponds.

Chemical amendment technologies appear to offer a unique benefit because they are capable of altering the properties of the clays responsible for fines formation and thus they offer a new dimension in dewatering technology. Chemical amendment may also be used to assist other dewatering methods. For example, the rate of sedimentation during mechanical thickening and centrifugation may be accelerated significantly by the use of coagulants and flocculants. The use of chemical additives has been studied for many years but this technology has not been accepted for reasons of operational practicability, cost-effectiveness and water quality. Recent research conducted on polymers has shown promise that this technology can be effective to dewater tailings. Suncor and Syncrude are using polymers in their centrifuge, thickener and evaporation/drying field tests to improve the performance of the technologies.

From the mixture/co-disposal group, only CT is operating commercially. However, operators have experienced difficulty making, transporting and placing on-spec CT; there is a tendency for the sand to segregate leaving a weak, low SFR material that is difficult to reclaim. The other issue is that supplemental sources of sand will likely be needed to treat the legacy MFT and CT requires a large containment area. CT is the most mature technology currently in practice. Suncor is planning to replace this technology with the TRO and MFT drying technology in the near future.

Pit lakes have been proposed to permanently store MFT, CT or TT creating self-sustaining aquatic ecosystems. This technology is in the commercial demonstration stage aiming to answer many uncertainties regarding function and success including water quality and toxicity, sustainability and liability.

4.3 Tailings Technology Gaps

Specific technology gaps for each technology were presented in Section 3 of this report. Below are listed general technology gaps identified in the overall tailings treatment processes (some of them proposed by Flint 2005):

- Quantifying and modeling fine tailings dispersion caused by the addition of sodium hydroxide in the CHWE process.
- Develop a unified sedimentation-consolidation model to predict settlement of material deposited in tailings ponds.
- MFT morphology and characteristics.
- Sand, clay, organics and water interactions in tailings.
- Role of chemical additives (polymers) in modifying tailings properties.
- Influence of chemical additives on water quality.
- Pumping of high solids content materials.
- Better mechanical dewatering means.
- Pond emission quantification, characterization and reduction.

5 CONCLUSIONS AND RECOMMENDATIONS

The search for a viable tailings dewatering technology will intensify as the already large quantities of liquid waste products generated by the oil sands industry grows and tailings storage facilities fill nearer to capacity. A review of the existing tailings technologies has led us to the conclusion that there is no single method of dewatering which works well for all tailings. Similarly, experience has shown that there is unlikely to be one unique solution to the problem of tailings disposal.

Many technologies have been suggested and tried but they have been rejected for lack of technical or economic feasibility. With no unique and acceptable solution yet in sight, research is now focusing on schemes which utilize more than one technology and combining them into a disposal package. Much of the recent work has been focused on field scale pilots supported by laboratory research.

6 GLOSSARY OF TERMS AND ACRONYMS IN THIS REPORT

The following terms and acronyms are used in this report.

6.1 Terms

Bitumen

A highly viscous tarry, black, hydrocarbon material having an API gravity of about nine degrees (a density of 1.0). Bitumen is the main product of the oil sands extraction process that is upgraded to synthetic crude oil.

Clearwater Formation (Kc)

A Cretaceous clayshale overburden exhibiting a medium to high plasticity and low moisture content.

Coagulant

A reagent (typically a calcium salt) added to a dispersion of solids in a liquid to bind together active minerals to form a continuous mass. This is the process used for making CT.

Coagulation

A process that causes aggregation of colloids by changing their surface characteristics or surface charge with coagulant.

Co-disposal

A placement of two or more tailings streams or tailings and overburden together.

Coke

A byproduct of upgrading bitumen to synthetic oil. At Syncrude it is a black fine-grained sand sized carbon particles with some sulphur and trace metals. Suncor has similar chemistry, but the coke is a sandy gravel. It is a potential source of energy.

Composite/Consolidated Tailings (CT)

A non-segregating mixture of chemically amended fine and coarse tailings which consolidates relatively quickly into solid landforms. The purpose of producing CT is to consume both legacy fines (MFT) and new fines (Thin Fine Tailings - TFT) to create a land surface reclaimable to upland or wetland vegetation. To this end, CT has a sand to fines ratio (SFR) that is greater than about 3:1 (to allow rapid consolidation) but less than about 5:1 (to permit useful levels of fines capture). CT starts as a slurry and ends as a semi-solid, loose, silty sand deposit that is dense enough and strong enough to support hydraulic sand capping.

Consolidation

The densification of fine-grained material by the release of excess pore-water pressure over time, typically in response to change in applied stress. For oil sands tailings, this process often involves slow settlement over time in response to self-weight or vertical surcharge from a capping layer. The expelled water is referred to as release water. Deposit strengths increase until full consolidation is reached. Many tailings materials remain soft even after full consolidation.

Cyclone Tailings

Hydrocyclones are used to classify (separate) oil sands slurry into a dense low-fines sandy underflow (Cyclone Underflow Tailings) and a low density, fines-rich cyclone overflow (Cyclone Overflow Tailings). The underflow may be beached or used as a feedstock for co-disposal with fines; the overflow is typically pumped to a settling basin.

Dam

The Canadian Dam Association (CDA) definition requires a dam to provide a fluid barrier that can impound 30,000 cubic metres or more and with a height of 2.5 metres or more. Fluid usually refers to water but may also refer to other liquids and potentially liquefiable materials (therefore tailings ponds berms are considered dams). To provide a maintenance free landscape, no structures that require monitoring and maintenance under CDA guidelines may be left behind.

Dedicated Disposal Area (DDA)

An area dedicated solely to the deposition of captured fines using a technology or suite of technologies (As defined by the Energy Resources Conservation Board in Directive 074).

Extraction

The process of separating bitumen from oil sand, typically with hot water and agitation.

Evapotranspiration

The term used to describe the sum of evaporation and plant transpiration from the earth's land surface to the atmosphere.

Filtered Tailings

Tailings that are processed by a technology involving mechanical dewatering by filtration (typically under pressure or vacuum). The tailings become unsaturated and are either conveyed or trucked to a disposal area.

Fine tailings

A suspension of fine silts, clays, residual bitumen and water derived from extraction of bitumen from oil sands using the traditional hot water extraction process. The remainder from the extraction process is pumped to tailings facilities where coarse sand settles out. The overflow is directed to a settling pond where the fine grained portion slowly settles to yield a suspension of fine tailings. The fine tailings suspension is typically 85% water and 15% fine particles by volume. Further dewatering of fine tailings occurs very slowly. When first discharged, the very low density material is referred to as thin fine tailings (TFT). After a year or two, when the fine tailings have reached a solids content of about 30% (by mass), they are referred to as mature fine tailings (MFT). Settling occurs much more slowly after this point and remains fluid-like for decades or centuries.

Fines

Grains of ore or tailings finer than 44 μm (typically measured as those passing the #325 wet sieve). Note that this is an oil sands specific definition of fines.

Fines Content

The ratio of the mass of dry fines (<44 μm) to mass of dry solids, expressed as a percent.

Floc

A loose-bound agglomeration of fine tailings particles typically around a polymer flocculant. These flocs, typically a few millimetres in diameter, settle quickly through

water. Subsequent consolidation and densification typically breaks down the polymer and the floc.

Froth

Air-entrained bitumen with a froth-like appearance that is the product of the primary extraction step in the warm or hot water extraction process.

Liquid Limit

The moisture content at which a soil changes from plastic to liquid behaviour and often corresponds to a peak vane shear strength of about 2 kPa.

Maintenance-free

Reclaimed land that is as sustainable as the original landscape without human intervention. It is recognized that natural erosion processes continually affect natural and reclaimed landscapes.

Oil Sands

A sand deposit containing bitumen in the pore space. Rich oil sands may contain up to 18% bitumen (weight basis) but mineable reserves often average 10% to 11% bitumen. Typical average orebody fines contents of mined or range from about 20% to 25%.

Pit Lake

An artificial lake within a mined out pit. In the oil sands region, some proposed pit lakes will be filled with varying amounts of tailings and capped with fresh water. Many such lakes are designed as bioreactors – allowing natural biodegradation of organic acids in the tailings waters.

Plastic Limit

The moisture content where a soil changes from plastic to semi-solid behaviour.

Process-affected Water

Water that has come in contact with oil sands, and may contain hydrocarbons, salts, and other chemicals.

Sand Content

The ratio of the mass of sand ($>44\ \mu\text{m}$) to mass of solids, expressed as a percentage.

Sand to Fines Ratio (SFR)

The mass of dry sand ($> 44\ \mu\text{m}$) to the mass of dry fines ($<44\ \mu\text{m}$).

Sedimentation or hindered sedimentation

A mode of densification when soil particles settle together en-masse through a water column. Unlike consolidation, during sedimentation there is no effective stress.

Shell

Shell Canada Energy

Soil-Water Characteristic Curve

The relationship between soil water content and soil water pressure potential (matric suction or negative pore water pressure). This curve is also referred to as the soil moisture retention curve and is important to unsaturated flow.

Solids Content

Ratio of the mass of dry solids to total mass of tailings, expressed as a percentage.

Suncor

Suncor Energy Inc.

Syncrude

Syncrude Canada Ltd.

Tailings

A by-product of oil sands extraction typically comprised of process water, sands, and clays, with minor amounts of residual bitumen – the oil sands with the “oil” removed.

Tailings Ponds

Man-made impoundment structures containing tailings. Tailings ponds are enclosed by dykes made with tailings and/or other mine waste materials to stringent geotechnical standards. Their function is to store solids and water and to act as a settling basin to clarify process water so it may be reused.

Thickening

The process of adding a flocculant to a tailings stream to cause the active minerals to bind together and settle rapidly.

Void Ratio (e)

The ratio of the volume of voids to the total volume of solids, typically expressed as a decimal.

Whole Tailings

Unaltered tailings that come directly from an extraction plant. Whole tailings is sometimes referred to as coarse tailings.

Wick Drain

A specific kind of vertical fabric drain that can be pushed into weak material at a spacing that allows more rapid consolidation and settlement. Also known as band drains.

6.2 Acronyms

AOS	Apparent Opening Sizes
AOSR	Athabasca Oil Sands Region
BGC	BGC Engineering Inc.
BML	Base Mine Lake (Syncrude)

CHWE	Clark Hot Water Extraction
COT	Cyclone Overflow Tailings
cP	Centipoise (a measure of viscosity – $10^{-2} \text{ g}^{-1} \text{ s}^{-1}$)
CPT	Cone Penetration Test
CT	Consolidated/Composite Tailings
CUT	Cyclone Underflow Tailings
DDA	Dedicated Disposal Area
EPL	End Pit Lake
ERCB	Energy Resources Conservation Board
ILTT	In-Line Thickened Tailings
kPa	kilopascals
LEE	Low Energy Extraction (Syncrude)
MFT	Mature Fine Tailings
NST	Non-Segregating Tailings
OCWE	OSLO Cold Water Extraction
OSRIN	Oil Sands Research and Information Network
PL	Pit Lake
PSV	Primary Separation Vessel
SFR	Sand to Fines Ratio
TFT	Thin Fine Tailings
TRO	Tailings Reduction Operation (Suncor)
TT	Thickened Tailings

7 REFERENCES

The references listed here are cited in the body of the report and in the Appendices. The numbers beside each reference are used in [Appendix 2](#).

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APPENDIX 1: Summary of Tailings Technologies

This Appendix contains four tables summarizing the 34 tailings technologies:

Table 1 – Descriptions of the technologies

Table 2 – Pros and cons of the technologies

Table 3 – Knowledge gaps for the technologies

Table 4 – State of technology development

Table 1: Brief description of each of the 34 technologies.

Tailings Treatment Technology		Description
Physical/Mechanical Processes	1. Filtered whole tailings	Filtration of the unaltered extraction tailings stream. Whole tailings are vacuum/pressure filtered in a filter plant and transported at low moisture content.
	2. Cross-flow filtration of whole tailings	Feed flow travels tangentially across the surface of the filter, rather than into the filter. Typically used for feeds with high fines content. Filter cake is washed away during filtration increasing length of time the filter unit can be operational.
	3. Filtered coarse tailings	Filtration and dry stacking of the coarse fraction (cyclone underflow) of the tailings slurry. Variants include adding some fines to the mix prior to filtration.
	4. Filter thickened fines tailings	Filtration and dry stacking of thickener underflow (predominantly fines). Other fine tailings streams are centrifuge fine tailings and MFT.
	5. Centrifuge fine tailings	A centrifuge applies up to thousands of times the force of gravity to extract fluid from material. The outlet stream yields solids at a density of about 60% solids. The other stream yields water, bitumen, and a minor amount of fines.
	6. Thermal drying MFT	Heating MFT in an oven / kiln to reduce the moisture content of MFT.
	7. Electrical treatment	Application of a direct current (DC) electric field to a clay slurry causes negatively charged clay particles to migrate to the positive (anode) electrode, resulting in accelerated sedimentation. There are three distinct electrokinetic transport mechanisms: electrophoresis, dielectrophoresis and electroosmosis.
	8. Blast densification	Explosive compaction is carried out by setting off explosive charges in the ground. The energy released causes liquefaction of the soil close to the blast point and causes cyclic straining of the soil. Liquefaction of the soil followed by time-dependent dissipation of the water pressures causes re-consolidation within the soil mass. "Short term" volume change is also caused by passage of the blast-induced shock front through the soil mass.
	9. Wick drains	Wick drains greatly facilitate the dewatering process by providing a suitable conduit to allow the pore water to escape very quickly. They are installed at close spacing shortening the flow path, and thereby expediting the consolidation process.
	10. Surcharge loading	Enhance consolidation of MFT or CT by application of a surcharge load (e.g. coke).
	11. CT under MFT	Deposition of CT under MFT to improve CT release water quality and probably the solids densification rates of both CT and MFT.
	12. Increase tailings density	Reduce segregation by increasing solids content of tailings sand slurry for beaching.
Natural Processes	13. Sedimentation/self-weight consolidation	Sedimentation is a gravity-settling of suspended solids from a liquid. As the concentration of solids particles in the sediment rises, the degree of inter-particle contact increases and dewatering by self-weight consolidation begins to take effect.
	14. Evaporation/drying	Deposition of MFT or CT in thin lifts and allowing the lifts to desiccate (remove moisture) by evaporative drying.
	15. Accelerated dewatering	Excavation of perimeter ditches (rim ditching) around a poulder of MFT or CT to promote drainage and evaporation. This technique lowers the water table of the deposit accelerating the consolidation process.
	16. Freeze/thaw	Deposition of MFT or CT in multiple thin layers which are allowed to freeze and then the frozen mass is allowed to thaw the following summer. The freeze-thaw cycle causes soil-like “peds” to form a structure which quickly consolidates.
	17. Plant (evapotranspiration) dewatering	The planting of grasses, shrubs or trees on CT may assist in dewatering (plant transpiration) and consolidation by the fibrous roots withdrawing water for growth.
Chemical/Biological Amendment	18. Thickening process	Using (polymer) flocculants in conjunction with mechanical thickeners to densify TFT or diluted MFT. Thickeners incorporate moving components, such as rakes, which shear flocs and promote removal of entrapped water.
	19. In-line thickened tailings (ILTT) technology	Injection and mixing of flocculants and coagulants into TFT stream in an in-line multi stage fashion. Conceptually by binding fine particles at low solids content into flocs, the hydraulic conductivity is increased, tortuousity is decreased and the mass of the falling flocs is increased. This process is aimed to improve settling and strength behavior of TFT.
	20. Whole tailings coagulation	A coagulant is added into the tailings pipeline to generate whole-tailings CT or partially segregating CT. Coagulants cause aggregation of colloids by changing their characteristics or surface charge.
	21. Whole tailings flocculation	Flocculants are added into the tailings pipeline to generate whole-tailings CT or partially segregating CT. Flocculants cause chemical bonding of colloids.
	22. In-situ biological treatment	Inoculation or enhancement of bacterial action to densify MFT or fine tailings. Methane production (methanogenesis), which is a biological activity accomplished by a consortium of anaerobic microbes, accelerates densification of MFT by generating channels in the tailings where gas bubbles rise.
	23. In-situ chemical treatment	Injection and mixing of chemical amendment to MFT in situ. Chemical additives injected in tailings ponds can increase the efficiency of the consolidation process by changing the pH or by promoting coagulation and/or flocculation.
	24. Reduce dispersion of fines in process	Change tailings water chemistry to reduce the amount of fines dispersion and trap more fines within the tailings sand.
Mixtures/Co-disposal	25. Composite/consolidated tailings (CT)	MFT is pumped from reservoirs and combined with cycloned tailings and a coagulant to produce a non-segregating slurry that consolidates over several decades and is strong enough and dense enough to allow hydraulic sand capping.
	26. MFT spiked tailings	Inject MFT into a coarse tailings stream to form a segregating slurry. Beaches trap higher proportion of clays and fines.
	27. Mixing MFT with Clearwater overburden	Mixing of Kc and MFT to form semi-solid mixes suitable for storage in polders. Water from MFT is absorbed by Kc resulting in a weaker, more plastic material.
	28. Mixing MFT with other overburden	Mixing of glacial materials (tills, clays, sands) and MFT to form a semi-solid mixture suitable for storage in polders.
	29. Mixing MFT with reclamation material	This technology consists of mixing MFT with peat moss to form a semi-solid mixture suitable for early reclamation.
	30. Mixing MFT/CT with coke	Mixing of MFT and coke to consolidate the more mobile tailings stream.
	31. Thickened tailings with sand	Mixing of thickened tailings and sand to form a non-segregating mix suitable for poldering.
Permanent Storage	32. MFT water capped lake	Permanently storing MFT under a water cap forming a lake which ultimately becomes a biologically active and self-sustaining functional ecosystem.
	33. Pit lake	Also known as End Pit Lake, is an engineered water body located below grade in oil sands post-mining pits. The pit lake will ultimately become a biologically active and self-sustaining functional ecosystem.
	34. Store MFT in underground caverns	Inject MFT in underground caverns or deep wells where future contact with human beings is unlikely.

Table 2: A list of the most relevant pros and cons of each technology.

Tailings Treatment Technology		Pros	Cons
Physical/Mechanical Processes	1. Filtered whole tailings	<ul style="list-style-type: none">• Requires a small footprint for tailings storage.• High recovery of process water.• Filtration produces “dry tailings” for stacking requiring no dam for retention.• Can be compacted.• Attractive to regulators.• Ease of progressive reclamation and closure of the facility, amenable to concurrent reclamation.• Low long-term liability in terms of structural integrity and potential environmental impacts.• Use of flocculants improves filterability significantly.• Dry tailings can be stacked at slopes greater than 10%.• No long-term consolidation settlements are expected because of the low moisture content. (Some post reclamation elastic or collapse settlements may still occur depending upon the density of the final deposit).	<ul style="list-style-type: none">• The process is costly due to the large amount of coagulant used and the high capital and operating costs for filtration equipment• Filtered tailings are no longer pumpable (low water content) and they need to be transported by conveyor or truck• Often more expensive per tonne of tailings stored than conventional slurry system, costly to truck and compact• The residual bitumen from extraction can clog the filters• Target only new tailings, not legacy MFT• Some reports indicate it is impractical to filter whole tailings with more than 4% fines without using flocculant• Challenging winter operations• Water quality may be affected by flocculants (if used).
	2. Cross-flow filtration of whole tailings	<ul style="list-style-type: none">• Higher dewatering rate is achieved by limiting cake thickness.• Process feed remains in the form of a mobile slurry, suitable for further processing.• Solids content of the product slurry may be varied over a wide range.• No chemical additive is required therefore no changes in the water chemistry.• Target both new tailings and legacy MFT.	<ul style="list-style-type: none">• Performance may be affected by the variability of whole tailings composition (fines content may affect performance).• Presence of residual bitumen may plug the membrane pores affecting performance.
	3. Filtered coarse tailings	<ul style="list-style-type: none">• Applicable without flocculants when fines content is less than 4%.• Viable method after flocculation for tailings with about 12% fines, which correspond to the sediment underflow from gravity settlers such a Primary Separation Vessel (PSV).• Low fines content can cause faster filtration and less blinding.• Operational costs are reduced if flocculants are not required. This may be only practical with low fines content (< 4% fines).• Results in a useful construction material with lower ionic contents.	<ul style="list-style-type: none">• Need to remove the fine fraction using a hydrocyclone or other methods.• Compaction or special handling procedures required for deposits.• High transport and deposition costs.
	4. Filter thickened fines tailings	<ul style="list-style-type: none">• Address legacy MFT.• Generate dry stack tailings with the benefits described in the previous technologies.	<ul style="list-style-type: none">• Filterability is relatively low, due to the high fines content.
	5. Centrifuge fine tailings	<ul style="list-style-type: none">• Requires relatively small storage area• Recover large amount of process water• Insensitive to bitumen fouling• Address legacy MFT• The solid bowl centrifuge is a continuous feed operation typically requiring reduced labour and operator effort• This technology is also noted as being the best technology for most oil, water, and latex sludge streams. Filter cake can be produced at a sufficiently high solids content to truck or convey to a reuse or to a final disposal site• As with most mechanical dewatering systems, the need for settling basins, return water systems and containment area reclamation, as well as the piping and pumps to the settling area is minimized or eliminated• Resulting deposit may be trafficable to specialized equipment and suitable for hydraulic sand capping or reclamation• Allows processing of tailings that is decoupled from the extraction process.	<ul style="list-style-type: none">• High upfront capital and operating costs• There may be issues with scale-up and trafficability (soft ground conditions can impede progress)• Transporting centrifuged cake may be challenging• Does not target new fines• Operation of a centrifuge requires a higher skill level and a more experienced operator• Requires a greater amount of electric power compared to filter press and belt press technologies• The solid bowl centrifuge functions as a secondary dewatering step necessitating a pre-thickening step; usually accomplished by a conventional thickener or clarifier. This technology must be considered a step in a more complex process and is not applicable as a stand-alone dewatering system.
	6. Thermal drying MFT	<ul style="list-style-type: none">• Thermal MFT drying eliminates water and diminishes the volume of the MFT by a factor of 4 to 5• It lowers the transportation cost and facilitates storage• Rapid removal of moisture in MFT.	<ul style="list-style-type: none">• Thermal drying is noted for its high-energy demand.
	7. Electrical treatment	<ul style="list-style-type: none">• Electrophoresis can be employed in the treatment of slurries• Electro-osmosis becomes significant when the slurry is gradually converted to a porous soil mass• Can be used in conjunction with surcharge loading and wick drains• Can also be combined with conventional filter presses.	<ul style="list-style-type: none">• Involves very high energy costs• Applicable to relatively narrow range of materials (primarily silts)• Difficulty in removing supernatant liquid• Problems with corrosion of the electrodes• Considered an ‘emerging’ technology with little-to-no plant-scale use or information available.
	8. Blast densification	<ul style="list-style-type: none">• Use to pack loose, saturated, medium to coarse sands• Eliminate the potential for liquefaction	<ul style="list-style-type: none">• Densification is not an instantaneous phenomenon• Possibility to damage nearby retention structures (dykes);• Requires monitoring (surveying, pore pressure)

Tailings Treatment Technology		Pros	Cons
	9. Wick drains	<ul style="list-style-type: none"> Accelerate the consolidation process reducing settlement times from years to months. Allows an accelerated placement of a final reclamation cover. Address legacy MFT/CT volumes. 	<ul style="list-style-type: none"> Wick drains may not retain their shape and integrity over time due to large settlement. As water is drained from the tailings, solid-like tailings begin to form around the wick drains and hence the hydraulic conductivity of these materials begins to impact flow rates in the wick drains. Clogging of wick drains. May require surcharge loading. Difficulty getting equipment onto the soft deposit. Costly due to close spacing of wick drains.
	10. Surcharge loading	<ul style="list-style-type: none"> Accelerates the dewatering process. Coke cap can be placed on top of MFT by sub-aqueous discharge. Use of geosynthetics can prevent mud wave but it is costly. Can be used with wick drains to accelerate consolidation. A few feet of surcharge is necessary to form a pad on which equipment can operate. Drainage blanket installed at the bottom can accelerate the dewatering process by applying a partial vacuum to the system. Allows for trafficability of the deposit. 	<ul style="list-style-type: none"> Difficult to place the surcharge cap on top of the MFT. Stability issues during cap placement (mud waves). Clogging of geotextile separation blankets remains a concern.
	11. CT under MFT	<ul style="list-style-type: none"> Improves quality of CT release water by reduction in the concentrations of calcium and sulphate ions, and the electrical conductivity. Improve CT and MFT densification rates 	<ul style="list-style-type: none"> Effects are modest
	12. Increase tailings sand density	<ul style="list-style-type: none"> High solids content slurry can be stacked at a significant slope and will promote dewatering by gravity drainage. The internal surcharge of coarse solids will accelerate the rate of dewatering of the contained fines. Formation of a partially segregating system. 	<ul style="list-style-type: none"> Difficulty in raising the solids content of a mix high enough to give a product which will stand on a slope, by blending existing slurries. Difficulty in pumping high solids content material. Surcharging (internal) does not significantly accelerate the rate of dewatering unless flocculants are added. Addition of solids, such as sand, only raises the solids content, not the viscosity (segregation is not eliminated). Equipment access may be an issue due to cyclic mobility (liquefaction) during trafficking.
Natural Processes	13. Sedimentation/self-weight consolidation	<ul style="list-style-type: none"> Tailings are pumped directly to a disposal area and are allowed to passively dewater while supernatant is decanted and recycled back into the process. Low cost, elimination of mechanical dewatering equipment necessitated by an accelerated process approach. Maintenance requirements and operator expertise are minimal as the approach is basic with limited technology. Robust in that it is effective for widely varying feed characteristics. 	<ul style="list-style-type: none"> Requires vast areas to provide sufficient storage. Engineered dams may be required, with the associated construction and maintenance costs. Pumping logistics are to be considered with the generally increased distance. Chemical treatment may be necessary to enhance rate of settlement. Relatively slow process which result in only partial dewatering.
	14. Evaporation/drying	<ul style="list-style-type: none"> Resulting surface is trafficable with modest equipment and suitable for additional layers for dewatering or sand capping and terrestrial reclamation. Post-reclamation settlement is expected to be small. Development of natural cracks as shrinkage occurs provides drainage channels for horizontal movement of water and additional surface area for evaporation. Tailings may be amended with chemical additives (polymers) to enhance dewatering and increase slope angles. 	<ul style="list-style-type: none"> Requires surface water management. Only thin layers can be treated and repeated through the summer. Large areas are required to treat large quantities. Need dyke structures (cell construction). Salt crusting or bitumen on the surface may reduce the evaporation rate. Vagaries of the weather can make this technology challenging to manage. Requires near-level sites to minimize earthwork. Labour intensive. High operational costs. Trafficability of final deposit is still only modest.
	15. Accelerated dewatering	<ul style="list-style-type: none"> Proven technology in Florida with phosphate tailings. Little intervention and low operational costs. Stand alone deposit. Potential MFT volume reduction of 50% after three to five years. Can be implemented in deep impoundments, 30 m plus. Formation of cracks accelerates the dewatering process. Resulting soft material can be suitably capped and reclaimed. 	<ul style="list-style-type: none"> Unproven in Alberta oil sands at commercial scale. Expensive chemical addition potentially needed to control bitumen fouling. Large up-front capital cost to build dykes. Requires additional disturbance footprint. Deepening of the rim ditches requires judgement and experience. Vagaries of the weather can make this technology challenging to manage. Labour intensive. Benches cut in the earth embankment are costly and time consuming.
	16. Freeze/thaw	<ul style="list-style-type: none"> Low upfront capital cost. Significant thickness can be treated by freezing subsequent layers on top of a previously frozen layer. Results in moderately low strength deposits up to 14 kPa in one year with low settlements. This may open up other reclamation options. Suitable for hydraulic sand capping as well. 	<ul style="list-style-type: none"> Thickness is related to how much can the thawed the following year (2 to 3m) Resulting material remains saturated and soft so is only suitable for hydraulic sand capping or reclamation using specialized equipment. Requires large areas and containment structures because of the thin fluid lifts. Managing the pumping of fluids during extremely cold temperatures is challenging. Labour intensive. Success subject to weather and operator diligence.
	17. Plant (evapotranspiration) dewatering	<ul style="list-style-type: none"> Suitable plant species can grow in tailings removing water by transpiration through the leaves. Plants transpire large quantities of water during the growing season. Absorption of CO₂ by plant. Root development increases bearing capacity at the tailings surface facilitating access of low pressure equipment for reclamation. Vegetation can assimilate minerals and various organic toxic compounds and much of this material can be removed by timely harvest. 	<ul style="list-style-type: none"> High salinity of tailings can inhibit establishment and healthy growth. Challenges getting seeds to develop in the deposit – work best with seedlings. Placement of fertilizer, seedlings/seeds and other amendments onto large deposits is not well developed. Depth of dewatering is limited by root depth. Concern regarding use of non-native and potentially invasive species.
Chemical/Biological Amendment	18. Thickening process	<ul style="list-style-type: none"> Targets new fines. Quickly recovers process water with its contained heat. Densifies the tailings outlet stream enhancing fines capture in sand deposits. The fines captured will not be available to make more MFT. Resulting material can be deposited with less land disturbance with the potential of accelerated land reclamation. Reduces groundwater concerns. Requires more modest containment. More stable deposits. High solids underflow from thickener. 	<ul style="list-style-type: none"> Resulting material is still a slurry requiring further treatment. Requires careful operational control and qualified operations staff. Does not address legacy MFT. Bitumen accumulation in the thickener feedwell can impair flocculation efficiency. High startup and operational costs, experienced operators needed. Long-term consolidation settlement. Adverse impacts of plant upset conditions. Tailings can only be stacked at slopes of 0.5% to 1%.
	19. In-line thickened tailings (ILTT) technology	<ul style="list-style-type: none"> Rapid dewatering of COT. Require a relatively small containment area to store ILTT. Undrained shear strength of ILTT is considerably higher than that of COT or MFT. The combination of the high hydraulic conductivity and the high undrained shear strength opens up other possible dewatering techniques. Reduce energy cost by returning water with its heat. No or little coagulant addition will be required to make CT from ILTT resulting in a reduction in cost and an increase in the quality of the recycle 	<ul style="list-style-type: none"> Floc disruption during tailings transportation can reduce ILTT’s high hydraulic conductivity and undrained shear strength. The advantage of being more permeable of ILTT can disappear at higher solids contents. Challenging to pump ILTT from depositional ponds and mix it with cyclone underflow tailings to make CT without a significant breakdown of the floc structure. Potential adverse impacts on water quality due to the addition of

Tailings Treatment Technology		Pros	Cons
		water. • Reduction of new MFT formation and storage.	coagulants and flocculants. • Requires increased operational control. • High operational cost.
	20. Whole tailings coagulation	• Resulting material may be suitable for vacuum or pressure filtration (not an economical method) or building beaches and slopes (less than 1% slope to minimize segregation). • Recovers large amounts of process water and reduces water capture in MFT. • Sedimentation and initial consolidation commence almost immediately after deposition and is complete within a short period of several days to a few weeks. • Captures new fines reducing MFT generation.	• Chemical reagents probably generate detrimental effects on recycle water quality. • High operational cost. • May need to be used with flocculants. • Potential adverse impacts on water quality due to the addition of coagulants and flocculants.
	21. Whole tailings flocculation	• Resulting material is suitable for vacuum or pressure filtration (not an economical method) or building beaches and slopes (less than 1% slope to minimize segregation). • Recovers large amount of process water. • Sedimentation and initial consolidation commence almost immediately after deposition and is complete within a short period of several days to a few weeks. • Hundreds of commercial flocculating reagents are available. • Addresses new fines.	• Unpredictable performance due to tailings variability. • Requires enhanced operational control/care. • Use of chemical reagents may generate possible detrimental effects on recycle water quality. • High operational cost. • May need to be used with coagulants.
	22. In-situ biological treatment	• Low cost. • Micro-biological activity produces carbon dioxide and methane leading to formation of gas pockets which coalesce to provide vertical drainage channels accelerating drainage and densification.	• Limited knowledge. • This process is difficult to control in a large scale. • Not proven technology. • Lack of understanding of microbes present in MFT.
	23. In-situ chemical treatment	• Chemical reagents can reverse the dispersive effects of caustic used in the extraction process. • Address legacy MFT. • Does not require additional footprint because the tailings are treated in situ.	• Limited knowledge on coagulants and flocculants. • Not proven technology. • Injecting and mixing in situ can be very challenging.
	24. Reduce dispersion of fines in process	• Dispersion is reduced by eliminating the use of sodium hydroxide in the extraction process. • Improves the energy efficiency, reducing operational costs. • Reduces the volume of process water. • Brings significant environmental benefits. • Produces a tailings effluent with better short-term consolidation properties. • Allows hydraulic sand capping soon after deposition and can subsequently be reclaimed to support terrestrial land uses.	• Contradicts the existing knowledge of bitumen extraction. • Lower bitumen extraction efficiency. • Does not appear to enhance long-term consolidation rates • Total volume of soft material increased substantially.
Mixtures/Co-disposal	25. Composite/ consolidated tailings (CT)	• Relatively low cost. • Operationally implemented at large scale. • Deals with legacy MFT. • Non-segregating tailings slurry. • Consolidates over a short time to form a solid landscape suitable for hydraulic sand capping and terrestrial reclamation. • Tailings management flexibility. • Consolidation rates for on-spec CT higher than expected.	• Requires robust system to deal with variability of feed. • Requires large containment until it solidifies (containment is expensive). • Low energy efficiency. • Operators have experienced difficulty in consistently depositing on-spec CT. Off-spec CT has consolidation properties similar to those of MFT. • Careful engineering and operation is required to prevent segregation during deposition. • Requires large amount of sand, supplemental source of sand will be needed to treat the legacy MFT. • Dosage of gypsum is quite large resulting in the buildup of calcium and sulphate ions in the recycle water which in time will negatively affect bitumen extraction. • Produces additional MFT from the cyclone overflow. • Potentially causes H ₂ S emissions by anaerobic reduction of SO ₄ ⁻² with the residual bitumen in the tailings. • Bulking up of material with poor consolidation characteristics.
	26. MFT spiked tailings	• Address legacy MFT • Practical and cost effective	• Trafficability of spiked beaches is marginal. • Additional fines in the deposits would also affect their rate of consolidation and this could influence the rate at which each lift could be built, as well as the ultimate height achievable safely.
	27. Mixing MFT with Clearwater overburden	• Clearwater formation contains a considerable amount of bentonite that can be blended with MFT to extract large amounts of water from the MFT. • Kc is abundant in overburden in the mineable oil sands area. • Avoids the use of costly chemicals and mechanical dewatering machines. • Process can be applied to any thickness (compared to technologies that rely on natural processes). • Resulting material deemed adequate for stacking. • High strength and rapid stabilization allows early access onto the deposit for reclamation.	• Controlling the deposition strategy to optimize the blending of the coarse and fine waste feeds is challenging. • It is only really economic where the two feeds can be pumped together or blended for in-pit storage. • The resulting mix would not be pumpable.
	28. Mixing MFT with other overburden	• More abundant overburden material to mix with MFT. • Similar to the technology in technology 27 but the glacial materials doesn't contain bentonite.	• Same as the technology 27 plus less capacity to uptake water from MFT than Kc.
	29. Mixing MFT with reclamation material	• Address legacy MFT. • Surface material will be ready for reclamation. • Reduces need for secondary reclamation material.	• Toxics compounds in MFT may inhibit plant growth. • Not proven technology. • Limited availability of reclamation material. • Expensive and likely unable to produce commercial forest.
	30. Mixing MFT with coke	• The mix may improve consolidation.	• Toxics compounds (nickel, vanadium and molybdenum) in coke may bioaccumulate in plants inhibiting their growth. • Coke, a source of energy, can be lost in a deposit or difficult to obtain if later required. • Benefits are unclear
	31. Mixing thickened tailings with sand	• The mixture has a high solids content and it may be stacked at a significant slope. • Address new fines. • May not require containment. • The high fines/high solids mix will have a high viscosity which will result in formation of a non-segregating system. • The internal surcharge of sand will raise the effective stress on the clay and promote self-weight consolidation.	• Not proven technology. • Improper application of this technique may result in the creation of reclaimed landforms of dubious environmental and economic value, particularly because of the presence of sodic clays and bituminous residues in oil sands tailings.
Permanent Storage	32. MFT water capped lake	• Low cost • Reduction of concentration of chemicals through natural microbial processes. • Self-sustaining aquatic ecosystem. • Geologic containment for fluid tailings where stored below original ground.	• Cannot be located where the body will recharge groundwater that may ultimately contact sensitive receptors. • Biological activity in the fluid tailings may emit considerable gas which may result in mixing fluid tailings with overlying water. • Regulators have not yet approved permanent storage of MFT under a water cap. Instead they have advocated for a solid trafficable landscape.
	33. Pit lake	• Same as technology 32.	• Same as technology 32.

Tailings Treatment Technology		Pros	Cons
	34. Store MFT in underground caverns	<ul style="list-style-type: none">• High costs, particularly if binders are used.• Tailings need to be dewatered, increasing costs.• Requires extra manpower and equipment.• Requires suitable location and development of caverns.	<ul style="list-style-type: none">• Need to evaluate volumes to be stored, adequate locations and costs.• Needs to evaluate suitability of this technique to be applied in the oil sands industry.

Table 3: Summary of the technology gaps and proposed areas of research.

Tailings Treatment Technology		Technology Gaps
Physical/Mechanical Processes	1. Filtered whole tailings	Optimize various polymer parameters: ionic type, charge density, molecular weight and dosage for a given tailings composition (fines content). Further study the impacts of polymers on water quality. Evaluate the filterability of tailings and filtration performance. Evaluate at large scale. Investigate filtration systems that can deal with bitumen fouling and high fines content.
	2. Cross-flow filtration of whole tailings	Further confirmation on influence of transmembrane pressure and tailings slurry velocity on the performance for various feeds (eg. various fines content) are required. Define variation of permeate flux and quality as well as cake characteristics along pipe length. Investigate whether this technology can be used effectively on TFT and MFT.
	3. Filtered coarse tailings	Optimize various polymer parameters: ionic type, charge density, molecular weight and dosage for a given tailings composition (fines content). Further study the impacts of polymers on water quality. Evaluate the filterability of tailings and filtration performance. Evaluate at large scale. Investigate filtration systems that can deal with bitumen fouling and high fines content.
	4. Filter thickened fines tailings	Need to identify polymers (flocculants, coagulants) that can deal with high fines content tailings and make the filtering more effective.
	5. Centrifuge fine tailings	Flocculant optimization. Cake transportation issues: conveyor and positive displacement pump. Need to evaluate centrifuge operational parameters and performance. Centrifuge scale-up studies. Need to further assess dewatering of centrifuged cake by natural processes and determination of optimal lift thickness.
	6. Thermal dry MFT	Environmental impact from vapor generated from the thermal drying.
	7. Electrical treatment	Need better understanding of electrokinetic. Need to research problems with corrosion of the electrodes. Collection and removal of water drained to the cathode.
	8. Blast densification	Need to understand time dependency process. Behaviour of fine tailings during blast densification
	9. Wick drains	Need to conduct large-scale tests to assess viability of this technology. Evaluate clogging of the wick drains in the field. Evaluate wick drain performance in conjunction with surcharge loading to accelerate dewatering. The mechanics of wicks is not well understood in materials that do not exhibit effective stress (high fines CT and MFT).
	10. Surcharge loading	Evaluate floating loading using geosynthetic reinforcement. Evaluate placement techniques for optimal implementation. Evaluate performance with wick drains to accelerate consolidation.
	11. CT under MFT	Further research is necessary in a controlled laboratory experiment to better understand the physical, chemical, and microbiological processes. This will help to assess the viability of implementing a full-scale field testing.
	12. Increase tailings sand density	This technique has not been favoured by the operators at the present time.
Natural Processes	13. Sedimentation/self-weight consolidation	Need to better understand the simultaneous process of sedimentation and consolidation from the physical and chemical point of view. Need a unified theoretical formulation.
	14. Evaporation/drying	Cell configuration including degree of slope, length and width. Cell management including MFT distribution, application rate, lift thickness, mechanical compaction, and release water control. Storage and preparation of polymer, including concentration and mixing with MFT. Effect of varying MFT maturities. Evaporation from cracked media.
	15. Accelerated dewatering	Need to engineer the operational method to implement it. Optimum polder thickness. Increase crack development. Improved understanding of drainage and evaporation processes, especially in cracked media.
	16. Freeze/thaw	Optimum lift thickness. Develop robust operational system.
	17. Plant (evapotranspiration) dewatering	Conduct small-scale pilot tests to assess viability of this technology using native species. Develop methods to place seedings, fertilizer and other amendments onto the deposit. Evaluate possibility of using in thin lifts similar to evaporation/drying. Buried vegetation will decay adding organic matter to the tailings. Evaluate performance in conjunction with freeze-thaw technology.
Chemical/Biological Amendment	18. Thickening process	Thickener feed preparation process, thickener type selection and thickening process. Flocculant selection and flocculation technology development. Contribution of raking mechanism to rate of dewatering. Thickened tailings transport (conveyor and positive displacement pump), deposition and consolidation. Reuse of thickener overflow water. Impacts on environment and existing plant operation.
	19. In-line thickening of fines (ILTT)	Further research is required to confirm the influence of shearing on segregation behaviour of CT made from ILTT under a dynamic condition. Viability at large-scale. Robustness of the technology with tailings variability. Quality of released water from the process. Shear thinning and methods to reduce its effects. Methods to treating MFT directly without dilution.
	20. Whole tailings coagulation	Understand the coagulation characteristics of whole tailings. A rheology modification chemical is required to facilitate the fines material integrating in the coarse structure.
	21. Whole tailings flocculation	Understanding the flocculation characteristics of whole tailings. Impact of bitumen and sand on flocculation process. Quality of released water from the process. Evaluation of flocculants should include clay mineralogy, age of the slurry, the method of flocculant introduction, the dilution of the slurry, the pH of the slurry, the mixing shear and the conditioning and contact time. A rheology modification chemical is required to facilitate the fines material integrating in the coarse structure.
	22. In-situ biological treatment	Need to understand the gas migration process through MFT and how it relates to consolidation of MFT. Also consolidation that may shut off the drainage channels has to be further studied. Better understanding of microbes present in MFT produced by different oil sands extraction operators. Need to identify roles that these microorganisms play in methanogenesis and MFT densification in the tailings ponds. Need to better quantify impact in MFT densification and its effectiveness in the long term.
	23. In-situ chemical treatment	Develop a systematic method to ensure adequate mixing. Understand required dosages and associated costs. Determine net potential impact/benefit. Need to identify roles of different chemical additives in modifying tailings properties.
	24. Reduce dispersion of fines in process	Evaluate segregation behaviour. Test additional additives to increase bitumen extraction efficiency. Evaluate sedimentation, consolidation and strength performance characteristics.
Mixtures/Co-disposal	25. Composite/consolidated tailings (CT)	Develop a robust operational system to make on-spec CT. Evaluate new amendments (alternative to gypsum) such as CO ₂ , alum and polymers. Methods to improve off-spec CT performance.
	26. MFT spiked tailings	Methods to increase fines capture without compromising trafficability. A better understanding of the role of fines from MFT versus the fines from whole tailings and the impact on spiked tailings geotechnical performance.
	27. Mixing MFT with Clearwater overburden	Quantification of mixing proportions depending on the material properties and how to obtain adequate mixing. Evaluate methods of transportation of the resulting mix.
	28. Mixing MFT with other overburden	Quantification of mixing proportions depending on the material properties and how to obtain adequate mixing. Evaluate methods of transportation of the resulting mix.

Tailings Treatment Technology		Technology Gaps
	29. Mixing MFT with reclamation material	Quantification of mixing proportions depending on the material properties and how to obtain adequate mixing. Evaluate methods of transportation of the resulting mix.
	30. Mixing MFT/CT with coke	Quantification of mixing proportions depending on the material properties. Understanding consolidation behaviour. Understanding depositional behaviour (i.e. segregation). Assessment of toxicity in different plant species.
	31. Mixing thickened tailings with sand	Deeper insight into the geotechnical properties of thickened tailings/sand mixes would assist full field-scale planning tests which are extremely expensive. Strength and consolidation behaviour of various mixtures of sand and thickened tailings are not known. Evaluate liquefaction potential.
Permanent Storage	32. MFT water capped lake	Uncertainties remain regarding function and success including water quality and toxicity, sustainability and liability. Accurate quantification of methane release from biodegradation needs to be addressed. Understand how gas production impacts long term water quality.
	33. End pit lake	Uncertainties remain regarding function and success including water quality and toxicity, sustainability and liability. Accurate quantification of methane release from biodegradation needs to be addressed. Understand how gas production impacts long term water quality.
	34. Store MFT in underground caverns	Need to evaluate volumes to be stored, adequate locations and costs. Needs to evaluate suitability of this technique to be applied in the oil sands industry.

Table 4: Graphical view of the stage of maturity of each technology. A full bar represents completion of a stage, while a partial bar represents a relative progression into another stage of maturity.

Tailings Treatment Technology		Stage of Technology			
		Basic Research	Applied Research & Demonstration	Commercial Demonstration	Mature (Operates Commercially)
Physical/Mechanical Processes	1. Filtered whole tailings				
	2. Cross-flow filtration of whole tailings				
	3. Filtered coarse tailings				
	4. Filter thickened fines tailings				
	5. Centrifuge fine tailings				
	6. Thermal drying MFT				
	7. Electrical treatment				
	8. Blast densification				
	9. Wick drains				
	10. Surcharge loading				
	11. CT under MFT				
	12. Increase tailings sand density				
Natural Processes	13. Sedimentation/self-weight consolidation				
	14. Evaporation/drying				
	15. Accelerated dewatering				
	16. Freeze/thaw				
	17. Plant dewatering				
Chemical/Biological Amendment	18. Thickening process				
	19. In-line thickened tailings (ILTT) technology				
	20. Whole tailings coagulation				
	21. Whole tailings flocculation				
	22. In-situ biological treatment				
	23. In-situ chemical treatment				
	24. Reduce dispersion of fines in process				
Mixtures/Co-disposal	25. Composite/consolidated tailings (CT)				
	26. MFT spiked tailings				
	27. Mixing MFT with Clearwater overburden				
	28. Mixing MFT with other overburden				
	29. Mixing MFT with reclamation material				
	30. Mixing MFT/CT with coke				
	31. Mixing thickened tailings with sand				
Permanent Storage	32. MFT water capped lake				
	33. Pit lake				
	34. Store MFT in underground caverns				

APPENDIX 2: Summaries of Each of the 34 Technologies

This Appendix contains tables summarizing each of the 34 technologies, providing:

- A short description
- Pros
- Cons
- State of technology
- Knowledge gaps
- Relative cost
- Comments
- List of relevant references (see Section 7)

1. Filtered whole tailings

Description:

Filtration of the unaltered extraction tailings stream. Whole tailings are vacuum/pressure filtered in a filter plant and transported at low moisture content. Filtering can take place using pressure or vacuum force. Drums, horizontally or vertically stacked plates and horizontal belts are the most common filtration plant configurations.

Pros:

- Requires a small footprint for tailings storage.
- High recovery of process water.
- Filtration produces “dry tailings” for stacking requiring no dam for retention.
- Can be compacted.
- Attractive to regulators.
- Ease of progressive reclamation and closure of the facility, amenable to concurrent reclamation.
- Low long-term liability in terms of structural integrity and potential environmental impacts.
- Use of flocculants improves filterability significantly.
- Dry tailings can be stacked at slopes greater than 10%.
- No long-term consolidation settlements are expected because of the low moisture content. (Some post reclamation elastic or collapse settlements may still occur depending upon the density of the final deposit).

Cons:

- The process is costly due to the large amount of coagulant used and the high capital and operating costs for filtration equipment
- Filtered tailings are no longer pumpable (low water content) and they need to be transported by conveyor or truck
- Often more expensive per tonne of tailings stored than conventional slurry system, costly to truck and compact
- The residual bitumen from extraction can clog the filters
- Target only new tailings, not legacy MFT
- Some reports indicate it is impractical to filter whole tailings with more than 4% fines without using flocculant
- Challenging winter operations
- Water quality may be affected by flocculants (if used).

Stage of technology: Applied research (mature in several non-oil sands tailings industries).

Knowledge gaps:

- Optimize various polymer parameters: ionic type, charge density, molecular weight and dosage for a given tailings composition (fines content)
- Further study the impacts of polymers on water quality
- Evaluate the filterability of tailings and filtration performance
- Evaluate at large scale
- Investigate filtration systems that can deal with bitumen fouling and high fines content

Relative Cost: High upfront capital and operational costs

Comments: Major area of tailings research worldwide. More common for small mines.

References: 4, 11, 39, 65, 85, 127, 178, 184

2. Cross-flow filtration of whole tailings

Description:

Cross-flow filtration gets its name because the majority of the feed flow travels tangentially across the surface of the filter, rather than into the filter. The main advantage of this is that a thickness of the [filter cake](#) (which can blind the filter) is substantially limited during the filtration process therefore the cross-flow filtration can be operated for a longer time compared to the other filtration methods. It can be a continuous process.

Pros:

- Higher dewatering rate is achieved by limiting cake thickness.
- Process feed remains in the form of a mobile slurry, suitable for further processing.
- Solids content of the product slurry may be varied over a wide range.
- No chemical additive is required therefore no changes in the water chemistry.
- Target both new tailings and legacy MFT.

Cons:

- Performance may be affected by the variability of whole tailings composition (fines content may affect performance).
- Presence of residual bitumen may plug the membrane pores affecting performance.

Stage of technology: Basic research.

Knowledge gaps

- It was found that increasing slurry velocity during cross-flow filtration operation can improve filtrate rate. Further confirmation on influence of transmembrane pressure and tailings slurry velocity on the performance for various feeds (eg. various fines content) are required.
- Define variation of permeate flux and quality as well as cake characteristics along pipe length.
- Investigate whether this technology can be used effectively on TFT and MFT.

Relative Cost:

High upfront capital and operational costs

Comments: This technology is currently being investigated at the University of Alberta

References: 4, 11, 39, 65, 70, 85, 127, 178, 184, 187

3. Filtered coarse tailings
<p>Description:</p> <p>Filtration and dry stacking of the coarse fraction (cyclone underflow) of the tailings slurry. Variants include adding some fines to the mix prior to filtration.</p>
<p>Pros:</p> <ul style="list-style-type: none"> • Applicable without flocculants when fines content is less than 4% (184). • Viable method after flocculation for tailings with about 12% fines, which correspond to the sediment underflow from gravity settlers such a Primary Separation Vessel (PSV) (184). • Low fines content can cause faster filtration and less blinding. • Operational costs are reduced if flocculants are not required. This may be only practical with low fines content (< 4% fines). • Results in a useful construction material with lower ionic contents.
<p>Cons:</p> <ul style="list-style-type: none"> • Need to remove the fine fraction using a hydrocyclone or other methods. • Compaction or special handling procedures required for deposits. • High transport and deposition costs.
<p>Stage of technology: Basic research and applied research and demonstration.</p>
<p>Knowledge gaps</p> <ul style="list-style-type: none"> • Optimize various polymer parameters: ionic type, charge density, molecular weight and dosage for a given tailings composition (fines content) • Further study the impacts of polymers on water quality • Evaluate the filterability of tailings and filtration performance • Evaluate at large scale • Investigate filtration systems that can deal with bitumen fouling and high fines content
<p>Relative Cost:</p> <p>High upfront and operational costs.</p>
<p>Comments: Syncrude eliminated this technology because it was deemed to have a low probability of success at Mildred Lake site (175).</p>
<p>References: 4, 11, 39, 65, 85, 127, 175, 178, 184</p>

4. Filtered thickened fines tailings	
Description:	Filtration and dry stacking of thickener underflow (predominantly fines). Other fine tailings streams are centrifuge fine tailings and MFT.
Pros:	<ul style="list-style-type: none"> • Address legacy MFT • Generate dry stack tailings with the benefits described in the previous technologies
Cons:	<ul style="list-style-type: none"> • Filterability is relatively low, due to the high fines content.
Stage of technology:	Basic research.
Knowledge gaps	<ul style="list-style-type: none"> • Need to identify polymers (flocculants, coagulants) that can deal with high fines content tailings and make the filtering more effective.
Relative Cost:	High upfront and operational costs.
Comments:	This technology has been proposed, but it seems impractical due to the high fines content.
References:	4, 11, 39, 65, 85, 127, 178, 184

5. Centrifuge fine tailings

Description:

A centrifuge applies up to thousands of times the force of gravity to extract fluid from material. The outlet stream yields solids at a density of about 60% solids. The other stream yields water, bitumen, and a minor amount of fines.

Pros:

- Requires relatively small storage area
- Recover large amount of process water
- Insensitive to bitumen fouling
- Address legacy MFT
- The solid bowl centrifuge is a continuous feed operation typically requiring reduced labour and operator effort
- This technology is also noted as being the best technology for most oil, water, and latex sludge streams. Filter cake can be produced at a sufficiently high solids content to truck or convey to a reuse or to a final disposal site
- As with most mechanical dewatering systems, the need for settling basins, return water systems and containment area reclamation, as well as the piping and pumps to the settling area is minimized or eliminated
- Resulting deposit may be trafficable to specialized equipment and suitable for hydraulic sand capping or reclamation
- Allows processing of tailings that is decoupled from the extraction process.

Cons:

- High upfront capital and operating costs
- There may be issues with scale-up and trafficability (soft ground conditions can impede progress)
- Transporting centrifuged cake may be challenging
- Does not target new fines
- Operation of a centrifuge requires a higher skill level and a more experienced operator
- Requires a greater amount of electric power compared to filter press and belt press technologies
- The solid bowl centrifuge functions as a secondary dewatering step necessitating a pre-thickening step; usually accomplished by a conventional thickener or clarifier. This technology must be considered a step in a more complex process and is not applicable as a stand-alone dewatering system.

Stage of technology: Applied research and demonstration.
Knowledge gaps <ul style="list-style-type: none"> • Flocculant optimization • Cake transportation issues: conveyor and positive displacement pump. • Need to evaluate centrifuge operational parameters and performance. • Centrifuge scale-up studies. • Need to further assess dewatering of centrifuged cake by natural processes and determination of optimal lift thickness.
Relative Cost: High upfront capital and operating costs
Comments: Syncrude is currently testing this technology.
References: 4, 16, 39, 49, 85, 87, 117, 120, 126, 127, 129

6. Thermal drying MFT

Description:

Heating MFT in an oven / kiln to reduce the moisture content of MFT. Thermal drying can remove water from sludge to a significantly higher degree than all other dewatering processes.

Pros:

- Thermal MFT drying eliminates water and diminishes the volume of the MFT by a factor of 4 to 5
- It lowers the transportation cost and facilitates storage
- Rapid removal of moisture in MFT.

Cons:

- Thermal drying is noted for its high-energy demand.

Stage of technology: Basic research.

Knowledge gaps

- Environmental impact from vapor generated from the thermal drying.

Relative Cost:

High upfront capital and operational costs.

Comments: No much interest in this technology.

References: 9, 39, 127

7. Electrical treatment

Description:

Application of a direct current (DC) electric field to a clay slurry causes negatively charged clay particles to migrate to the positive (anode) electrode, resulting in accelerated sedimentation. There are three distinct electrokinetic transport mechanisms: electrophoresis, dielectrophoresis, and electro-osmosis.

Pros:

- Electrophoresis can be employed in the treatment of slurries
- Electro-osmosis becomes significant when the slurry is gradually converted to a porous soil mass
- Can be used in conjunction with surcharge loading and wick drains
- Can also be combined with conventional filter presses.

Cons:

- Involves very high energy costs
- Applicable to relatively narrow range of materials (primarily silts)
- Difficulty in removing supernatant liquid
- Problems with corrosion of the electrodes
- Considered an 'emerging' technology with little-to-no plant-scale use or information available.

Stage of technology: Basic research.

Knowledge gaps:

- Need better understanding of electrokinetic
- Need to research problems with corrosion of the electrodes
- Collection and removal of water drained to the cathode.

Relative Cost:

Low upfront capital cost, but high operational cost.

Comments: In recent years there has been an interest in the possible combination of surcharge preloading, vertical drains, and electro-osmosis to consolidate clay soils.

References: 54, 56, 98, 124, 154, 155, 156, 157, 158, 165

8. Blast densification

Description:

Explosive compaction is carried out by setting off explosive charges in the ground. The energy released causes liquefaction of the soil close to the blast point and causes cyclic straining of the soil. Liquefaction of the soil followed by time-dependent dissipation of the water pressures causes re-consolidation within the soil mass. "Short term" volume change is also caused by passage of the blast-induced shock front through the soil mass.

Pros:

- Use to pack loose, saturated, medium to coarse sands
- Eliminate the potential for liquefaction

Cons:

- Densification is not an instantaneous phenomenon
- Possibility to damage nearby retention structures (dykes);
- Requires monitoring (surveying, pore pressure)

Stage of technology: Basic research.

Knowledge gaps:

- Need to understand time dependency process.
- Behaviour of fine tailings during blast densification

Relative Cost:

Low

Comments:

This technology was used at Suncor site in 1991.

References: 55, 61, 84

9. Wick drains

Description:

Wick drains greatly facilitate the dewatering process by providing a suitable conduit to allow the pore water to escape very quickly. They are installed at close spacing shortening the flow path, and thereby expediting the consolidation process.

Pros:

- Accelerate the consolidation process reducing settlement times from years to months.
- Allows an accelerated placement of a final reclamation cover.
- Address legacy MFT/CT volumes.

Cons:

- Wick drains may not retain their shape and integrity over time due to large settlement.
- As water is drained from the tailings, solid-like tailings begin to form around the wick drains and hence the hydraulic conductivity of these materials begins to impact flow rates in the wick drains.
- Clogging of wick drains.
- May require surcharge loading.
- Difficulty getting equipment onto the soft deposit.
- Costly due to close spacing of wick drains.

Stage of technology: Applied research and commercial demonstration.

Knowledge gaps:

- Need to conduct large-scale tests to assess viability of this technology.
- Evaluate clogging of the wick drains in the field.
- Evaluate wick drain performance in conjunction with surcharge loading to accelerate dewatering.
- The mechanics of wicks is not well understood in materials that do not exhibit effective stress (high fines CT and MFT).

Relative Cost:

High upfront capital cost.

Comments:

Suncor is currently testing this technology.

References: 3, 18, 33, 156, 179

10. Surcharge loading

Description:

Enhance consolidation of MFT or CT by application of a surcharge load (e.g. coke).

Pros:

- Accelerates the dewatering process.
- Coke cap can be placed on top of MFT by sub-aqueous discharge.
- Use of geosynthetics can prevent mud wave but it is costly.
- Can be used with wick drains to accelerate consolidation.
- A few feet of surcharge is necessary to form a pad on which equipment can operate.
- Drainage blanket installed at the bottom can accelerate the dewatering process by applying a partial vacuum to the system.
- Allows for trafficability of the deposit.

Cons:

- Difficult to place the surcharge cap on top of the MFT.
- Stability issues during cap placement (mud waves).
- Clogging of geotextile separation blankets remains a concern.

Stage of technology: Applied research and commercial demonstration.

Knowledge gaps

- Evaluate floating loading using geosynthetic reinforcement.
- Evaluate placement techniques for optimal implementation.
- Evaluate performance with wick drains to accelerate consolidation.

Relative Cost:

Low

Comments:

Suncor is currently conducting field trials.

References: 3, 35, 73, 74, 181

11. CT under MFT	
Description:	Deposition of CT under MFT to improve CT release water quality and probably the solids densification rates of both CT and MFT.
Pros:	<ul style="list-style-type: none"> Improves quality of CT release water by reduction in the concentrations of calcium and sulphate ions, and the electrical conductivity. Improve CT and MFT densification rates
Cons:	<ul style="list-style-type: none"> Effects are modest
Stage of technology:	Basic research.
Knowledge gaps	<ul style="list-style-type: none"> Further research is necessary in a controlled laboratory experiment to better understand the physical, chemical, and microbiological processes. This will help to assess the viability of implementing full-scale field testing.
Relative Cost:	Low
Comments:	
References:	105

12. Increase tailings sand density

Description:

This technique aims to reduce segregation by increasing solids content of tailings sand slurries in the pipeline prior to beaching.

Pros:

- High solids content slurry can be stacked at a significant slope and will promote dewatering by gravity drainage.
- The internal surcharge of coarse solids will accelerate the rate of dewatering of the contained fines.
- Formation of a partially segregating system.

Cons:

- Difficulty in raising the solids content of a mix high enough to give a product which will stand on a slope, by blending existing slurries.
- Difficulty in pumping high solids content material.
- Surcharging (internal) does not significantly accelerate the rate of dewatering unless flocculants are added.
- Addition of solids, such as sand, only raises the solids content, not the viscosity (segregation is not eliminated).
- Equipment access may be an issue due to cyclic mobility (liquefaction) during trafficking.

Stage of Technology: Basic research.

Knowledge gaps:

- This technique has not been favoured at the present time.

Relative Cost:

Low to medium

Comments:

References: None.

13. Sedimentation/self-weight consolidation

Description:

Sedimentation is a gravity-settling of suspended solids from a liquid. As the concentration of solids particles in the sediment rises, the degree of inter-particle contact increases and dewatering by self-weight consolidation begins to take effect.

Pros:

- Tailings are pumped directly to a disposal area and are allowed to passively dewater while supernatant is decanted and recycled back into the process.
- Low cost, elimination of mechanical dewatering equipment necessitated by an accelerated process approach.
- Maintenance requirements and operator expertise are minimal as the approach is basic with limited technology.
- Robust in that it is effective for widely varying feed characteristics.

Cons:

- Requires vast areas to provide sufficient storage.
- Engineered dams may be required, with the associated construction and maintenance costs.
- Pumping logistics are to be considered with the generally increased distance.
- Chemical treatment may be necessary to enhance rate of settlement.
- Relatively slow process which result in only partial dewatering.

Stage of technology: Mature (operates commercially).

Knowledge Gaps

- Need to better understand the interparticle forces inhibiting MFT to dewater to higher solids content.
- Sedimentation and consolidation analysis is of great practical importance in slurry handling processes. Sedimentation and consolidation phenomena are conventionally treated as two separate processes although in practice the phenomena are interconnected and there is a need to analyze them together.
- An improved fundamental understanding of the fluid to soil transition and the concomitant strength development will lead to better design and management of tailings facilities. Both sedimentation and consolidation phenomena are reciprocally recognized but a unified theoretical formulation that can correctly capture a transformation from sedimentation to consolidation does not exist yet and current practice is often based on empiricism.

Relative Cost: Low

Comments:

Currently used in the oil sands industry.

References: 3, 5, 7, 10, 13, 17, 19, 24, 35, 36, 39, 40, 41, 42, 43, 65, 67, 73, 74, 77, 97, 111, 116, 127, 133, 134, 137, 146, 148, 168, 169, 170, 171, 172, 176, 183

14. Evaporation/drying

Description:

Deposition of MFT in thin lifts and allowing the lifts to dissipate by evaporative drying. Tailings form a relatively high strength crust. Tailings may be amended with a coagulant to enhance dewatering and increase slope angles.

Pros:

- Resulting surface is trafficable with modest equipment and suitable for additional layers for dewatering or sand capping and terrestrial reclamation.
- Post-reclamation settlement is expected to be small.
- Development of natural cracks as shrinkage occurs provides drainage channels for horizontal movement of water and additional surface area for evaporation.
- Tailings may be amended with chemical additives (polymers) to enhance dewatering and increase slope angles.

Cons:

- Requires surface water management.
- Only thin layers can be treated and repeated through the summer.
- Large areas are required to treat large quantities.
- Need dyke structures (cell construction).
- Salt crusting or bitumen on the surface may reduce the evaporation rate.
- Vagaries of the weather can make this technology challenging to manage.
- Requires near-level sites to minimize earthwork.
- Labour intensive.
- High operational costs.
- Trafficability of final deposit is still only modest.

Stage of technology: Applied research and demonstration.

Knowledge gaps

- Cell configuration including degree of slope, length and width.
- Cell management including MFT distribution, application rate, lift thickness, mechanical compaction, and release water control.
- Storage and preparation of polymer, including concentration and mixing with MFT.
- Effect of varying MFT constituents and/or solids.
- Evaporation from cracked media

Relative Cost: High operational cost

Comments:

Suitable for modest volumes, but being considered for larger volumes by some operators.

References: 1, 10, 39, 58, 65, 91, 112, 127, 128, 139, 140, 152, 159, 180

15. Accelerated dewatering

Description:

Excavation of perimeter ditches (rim ditching) around a poulder of MFT or CT to promote drainage and evaporation. This technique lowers the water table of the deposit accelerating the consolidation process.

Pros:

- Proven technology in Florida with phosphate tailings.
- Little intervention and low operational costs.
- Stand alone deposit.
- Potential MFT volume reduction of 50% after three to five years.
- Can be implemented in deep impoundments, 30 m plus (86).
- Formation of cracks accelerates the dewatering process.
- Resulting soft material can be suitably capped and reclaimed.

Cons:

- Unproven in Alberta oil sands at commercial scale.
- Expensive chemical addition potentially needed to control bitumen fouling.
- Large up-front capital cost to build dykes.
- Requires additional disturbance footprint.
- Deepening of the rim ditches requires judgement and experience.
- Vagaries of the weather can make this technology challenging to manage.
- Labour intensive.
- Benches cut in the earth embankment are costly and time consuming.

Stage of technology: Applied research and demonstration, mature elsewhere

Knowledge gaps:

- Need to engineer the operational method to implement it at large/commercial scale.
- Optimization of impoundment thickness.
- Research should be directed at accelerating the formation of the cracks in the MFT.
- Improved understanding of drainage and evaporation processes, especially in cracked media.

Relative Cost:

Low to medium

Comments:

Syncrude is currently testing this technology.

References: 1, 10, 21, 22, 49, 58, 87, 91, 128

16. Freeze-Thaw

Description:

Deposition of MFT or CT in multiple thin layers which are allowed to freeze and then the frozen mass is allowed to thaw the following summer. The freeze-thaw cycle causes soil-like “peds” to form a structure which quickly consolidates.

Pros:

- Low upfront capital cost.
- Significant thickness can be treated by freezing subsequent layers on top of a previously frozen layer.
- Results in moderately low strength deposits up to 14 kPa in one year (37, 135) with low settlements. This may open up other reclamation options. Suitable for hydraulic sand capping as well.

Cons:

- Thickness is related to how much can be thawed the following year (2 to 3m)
- Resulting material remains saturated and soft so is only suitable for hydraulic sand capping or reclamation using specialized equipment.
- Requires large areas and containment structures because of the thin fluid lifts.
- Managing the pumping of fluids during extremely cold temperatures is challenging.
- Labour intensive.
- Success subject to weather and operator diligence.

Stage of technology: Applied research and demonstration.

Knowledge gaps

- Optimum lift thickness.
- Understanding the likely final solids content/consistency in large scale applications to develop effective reclamation strategies.
- Development of a robust operational system.

Relative Cost:

Low upfront capital cost. High operational costs.

Comments:

Suitable for modest volumes, but being considered for larger volumes by some operators. The scale of tailings and pond operations means that any use of freezing and thawing cycles is through use of the natural seasonal cycles. Freezing and thawing presents the opportunity to release more water from tailings streams, and to separate salts from water.

References: 10, 37, 38, 39, 59, 60, 80, 127, 130, 135, 136, 151, 152, 153

17. Plant (evapotranspiration) dewatering

Description:

The planting of grasses, shrubs or trees on CT may assist in dewatering (plant transpiration) and consolidation by the fibrous roots withdrawing water for growth.

Pros:

- Suitable plant species can grow in tailings removing water by transpiration through the leaves.
- Plants transpire large quantities of water during the growing season.
- Absorption of CO₂ by plant.
- Root development increases bearing capacity at the tailings surface facilitating access of low pressure equipment for reclamation.
- Vegetation can assimilate minerals and various organic toxic compounds and much of this material can be removed by timely harvest.

Cons:

- High salinity of tailings can inhibit establishment and healthy growth.
- Challenges getting seeds to develop in the deposit – work best with seedlings.
- Placement of fertilizer, seedlings/seeds and other amendments onto large deposits is not well developed.
- Depth of dewatering is limited by root depth.
- Concern regarding use of non-native and potentially invasive species.

Stage of technology: Basic research. Previous applied research and development were conducted in the field (79).

Knowledge gaps

- Conduct small-scale pilot tests to assess viability of this technology using native species.
- Develop methods to place seedlings, fertilizer and other amendments onto the deposit.
- Evaluate possibility of using in thin lifts similar to evaporation/drying. Buried vegetation will decay adding organic matter to the tailings.
- Evaluate performance in conjunction with freeze-thaw technology.

Relative Cost:

Low upfront capital cost. High operational costs.

Comments:

Previous field trials were conducted (Johnson et al. 1993)

References: 1, 10, 14, 15, 31, 39, 63, 80, 93, 94, 127, 141, 142, 145, 150, 152, 162

18. Thickening process

Description:

Using (polymer) flocculants in conjunction with mechanical thickeners to densify TFT or diluted MFT. Thickeners incorporate moving components, such as rakes, which shear flocs and promote removal of entrapped water.

Pros:

- Targets new fines.
- Quickly recovers process water with its contained heat.
- Densifies the tailings outlet stream enhancing fines capture in sand deposits. The fines captured will not be available to make more MFT.
- Resulting material can be deposited with less land disturbance with the potential of accelerated land reclamation.
- Reduces groundwater concerns.
- Requires more modest containment.
- More stable deposits.
- High solids underflow from thickener.

Cons:

- Resulting material is still a slurry requiring further treatment.
- Requires careful operational control and qualified operations staff.
- Does not address legacy MFT.
- Bitumen accumulation in the thickener feedwell can impair flocculation efficiency.
- High startup and operational costs, experienced operators needed.
- Long-term consolidation settlement.
- Adverse impacts of plant upset conditions.
- Tailings can only be stacked at slopes of 0.5% to 1%.

Stage of technology: Applied research and demonstration, mature elsewhere.

Knowledge gaps

- Thickener feed preparation process, thickener type selection and thickening process.
- Flocculant selection and flocculation technology development.
- Contribution of raking mechanism to rate of dewatering.
- Thickened tailings transport (conveyor and positive displacement pump), deposition and consolidation.
- Reuse of thickener overflow water.
- Impacts on environment and existing plant operation.

Relative Cost:
High upfront and operational costs.
Comments:
A number of operators are testing this technology.
References: 4, 6, 16, 26, 32, 49, 65, 79, 85, 89, 90, 99, 101, 113, 127, 138, 143, 144, 159, 173, 174, 182, 185, 186

19. In-line thickened tailings (ILTT) technology

Description:

Injection and mixing of flocculants and coagulants into TFT stream in an in-line multi stage fashion. Conceptually by binding fine particles at low solids content into flocs, the hydraulic conductivity is increased, tortuosity is decreased and the mass of the falling flocs is increased. This process is aimed to improve settling and strength behavior of TFT.

Pros:

- Rapid dewatering of COT.
- Require a relatively small containment area to store ILTT.
- Undrained shear strength of ILTT is considerably higher than that of COT or MFT. The combination of the high hydraulic conductivity and the high undrained shear strength opens up other possible dewatering techniques.
- Reduce energy cost by returning water with its heat.
- No or little coagulant addition will be required to make CT from ILTT resulting in a reduction in cost and an increase in the quality of the recycle water.
- Reduction of new MFT formation and storage.

Cons:

- Floc disruption during tailings transportation can reduce ILTT's high hydraulic conductivity and undrained shear strength.
- The advantage of being more permeable of ILTT can disappear at higher solids contents.
- Challenging to pump ILTT from depositional ponds and mix it with cyclone underflow tailings to make CT without a significant breakdown of the floc structure.
- Potential adverse impacts on water quality due to the addition of coagulants and flocculants.
- Requires increased operational control.
- High operational cost.

Stage of technology: Applied research and demonstration.

Knowledge gaps

- Further research is required to confirm the influence of shearing on segregation behaviour of CT made from ILTT under a dynamic condition.
- Viability at large-scale.
- Robustness of the technology with tailings variability.
- Quality of released water from the process.
- Shear thinning and methods to reduce its effects.
- Methods to treating MFT directly without dilution

Relative Cost: High upfront capital and operational costs.

References: 4, 6, 16, 32, 65, 75, 76, 78, 85, 99, 159

20. Whole tailings coagulation

Description:

A coagulant is added into the tailings pipeline to generate whole-tailings CT or partially segregating CT. Coagulants cause aggregation of colloids by changing their characteristics or surface charge.

Pros:

- Resulting material may be suitable for vacuum or pressure filtration (not an economical method) or building beaches and slopes (less than 1% slope to minimize segregation).
- Recovers large amounts of process water and reduces water capture in MFT.
- Sedimentation and initial consolidation commence almost immediately after deposition and is complete within a short period of several days to a few weeks.
- Captures new fines reducing MFT generation.

Cons:

- Chemical reagents probably generate detrimental effects on recycle water quality.
- High operational cost.
- May need to be used with flocculants.
- Potential adverse impacts on water quality due to the addition of coagulants and flocculants.

Stage of technology: Applied research and demonstration.

Knowledge gaps

- Understand the coagulation characteristics of whole tailings.
- A rheology modification chemical is required to facilitate the fines material integrating in the coarse structure.

Relative Cost:

High upfront and operational costs.

Comments:

References: 32, 65, 85, 90, 99, 159, 173, 174

21. Whole tailings flocculation

Description:

Flocculants are added into the tailings pipeline to generate whole-tailings CT or partially segregating CT. Flocculants cause chemical bonding of colloids.

Pros:

- Resulting material is suitable for vacuum or pressure filtration (not an economical method) or building beaches and slopes (less than 1% slope to minimize segregation).
- Recovers large amount of process water.
- Sedimentation and initial consolidation commence almost immediately after deposition and is complete within a short period of several days to a few weeks.
- Hundreds of commercial flocculating reagents are available.
- Addresses new fines.

Cons:

- Unpredictable performance due to tailings variability.
- Requires enhanced operational control/care.
- Use of chemical reagents may generate possible detrimental effects on recycle water quality.
- High operational cost.
- May need to be used with coagulants.

Stage of technology: Applied research and demonstration.

Knowledge gaps

- Understanding the flocculation characteristics of whole tailings.
- Impact of bitumen and sand on flocculation process.
- Quality of released water from the process.
- Evaluation of flocculants should include clay mineralogy, age of the slurry, the method of flocculant introduction, the dilution of the slurry, the pH of the slurry, the mixing shear and the conditioning and contact time.
- A rheology modification chemical is required to facilitate the fines material integrating in the coarse structure.

Relative Cost:

High upfront and operational costs.

Comments:

References: 32, 39, 65, 66, 85, 90, 99, 127, 138, 149, 159, 173, 174

22. In-situ biological treatment

Description:

Inoculation or enhancement of bacterial action to densify MFT or fine tailings. Methane production (methanogenesis), which is a biological activity accomplished by a consortium of anaerobic microbes, accelerates densification of mature fine tailings (MFT) by generating channels in the tailings where gas bubbles rise.

Pros:

- Low cost.
- Micro-biological activity produces carbon dioxide and methane leading to formation of gas pockets which coalesce to provide vertical drainage channels accelerating drainage and densification.

Cons:

- Limited knowledge.
- This process is difficult to control in a large scale.
- Not proven technology.
- Lack of understanding of microbes present in MFT.

Stage of technology: Basic research.

Knowledge gaps

- Need to understand the gas migration process through MFT and how it relates to consolidation of MFT. Also consolidation that may shut off the drainage channels has to be further studied.
- Better understanding of microbes present in MFT produced by different oil sands extraction operators.
- Need to identify roles that these microorganisms play in methanogenesis and MFT densification in the tailings ponds.
- Need to better quantify impact in MFT densification and its effectiveness in the long term.

Relative Cost:

Low upfront and operational costs.

Comments:

References: 50, 64, 68, 88

23. In-situ chemical treatment

Description:

Injection and mixing of chemical amendment to MFT in situ. Chemical additives injected in tailings ponds can increase the efficiency of the consolidation process by changing the pH or by promoting coagulation and/or flocculation.

Pros:

- Chemical reagents can reverse the dispersive effects of caustic used in the extraction process.
- Address legacy MFT.
- Does not require additional footprint because the tailings are treated in situ.

Cons:

- Limited knowledge on coagulants and flocculants.
- Not proven technology.
- Injecting and mixing in situ can be very challenging.

Stage of technology: Basic research.

Knowledge gaps

- Develop a systematic method to ensure adequate mixing.
- Understand required dosages and associated costs.
- Determine net potential impact/benefit.
- Need to identify roles of different chemical additives in modifying tailings properties.

Relative Cost:

Low upfront and operational costs.

Comments:

References: 32, 65, 83, 85, 99

24. Reduce dispersion of fines in process

Description:

Change tailings water chemistry to reduce the amount of fines dispersion and trap more fines within the tailings sand.

Pros:

- Dispersion is reduced by eliminating the use of sodium hydroxide in the extraction process.
- Improves the energy efficiency, reducing operational costs.
- Reduces the volume of process water.
- Brings significant environmental benefits.
- Produces a tailings effluent with better short-term consolidation properties.
- Allows hydraulic sand capping soon after deposition and can subsequently be reclaimed to support terrestrial land uses.

Cons:

- Contradicts the existing knowledge of bitumen extraction.
- Lower bitumen extraction efficiency.
- Does not appear to enhance long-term consolidation rates
- Total volume of soft material increased substantially.

Stage of technology: Commercial demonstration and mature.

Knowledge gaps

- Evaluate segregation behaviour.
- Test additional additives to increase bitumen extraction efficiency.
- Evaluate sedimentation, consolidation and strength performance characteristics.

Relative Cost:

High

Comments:

This technology is used by Syncrude in its Low Energy Extraction process.

References: 5, 86, 132, 133, 134

25. Composite/consolidated (CT) tailings

Description:

MFT is pumped from reservoirs and combined with cycloned tailings and a coagulant to produce a non-segregating slurry that consolidates over several decades and is strong enough and dense enough to allow hydraulic sand capping.

Pros:

- Relatively low cost.
- Operationally implemented at large scale.
- Deals with legacy MFT.
- Non-segregating tailings slurry.
- Consolidates over a short time to form a solid landscape suitable for hydraulic sand capping and terrestrial reclamation.
- Tailings management flexibility.
- Consolidation rates for on-spec CT higher than expected.

Cons:

- Requires robust system to deal with variability of feed.
- Requires large containment until it solidifies (containment is expensive).
- Low energy efficiency.
- Operators have experienced difficulty in consistently depositing on-spec CT. Off-spec CT has consolidation properties similar to those of MFT.
- Careful engineering and operation is required to prevent segregation during deposition.
- Requires large amount of sand, supplemental source of sand will be needed to treat the legacy MFT.
- Dosage of gypsum is quite large resulting in the buildup of calcium and sulphate ions in the recycle water which in time will negatively affect bitumen extraction.
- Produces additional MFT from the cyclone overflow.
- Potentially causes H₂S emissions by anaerobic reduction of SO₄⁻² with the residual bitumen in the tailings.
- Bulking up of material with poor consolidation characteristics.

Stage of technology: Mature (operates commercially).

Knowledge gaps

- Develop a robust operational system to make on-spec CT.
- Evaluate new amendments (alternative to gypsum) such as CO₂, alum and polymers.
- Methods to improve off-spec CT performance.

Relative Cost: Low

References: 7, 17, 19, 23, 24, 27, 39, 41, 44, 97, 108, 110, 112, 114, 118, 119, 127, 137, 159

26. MFT spiked tailings

Description:

Inject MFT into a coarse tailings stream to form a segregating slurry. Beaches trap higher proportion of clays and fines.

Pros:

- Address legacy MFT
- Practical and cost effective

Cons:

- Trafficability of spiked beaches is marginal.
- Additional fines in the deposits would also affect their rate of consolidation and this could influence the rate at which each lift could be built, as well as the ultimate height achievable safely.

Stage of technology: Applied research.

Knowledge gaps

- Methods to increase fines capture without compromising trafficability
- A better understanding of the role of fines from MFT versus the fines from whole tailings and the impact on spiked tailings geotechnical performance.

Relative Cost:

Low

Comments:

References: 7, 34

27. Mixing MFT with clearwater overburden

Description:

Mixing of Kc and MFT to form semi-solid mixes suitable for storage in polders. Water from MFT is absorbed by Kc resulting in a weaker, more plastic material.

Pros:

- Clearwater formation contains a considerable amount of bentonite that can be blended with MFT to extract large amounts of water from the MFT.
- Kc is abundant in overburden in the mineable oil sands area.
- Avoids the use of costly chemicals and mechanical dewatering machines.
- Process can be applied to any thickness (compared to technologies that rely on natural processes).
- Resulting material deemed adequate for stacking.
- High strength and rapid stabilization allows early access onto the deposit for reclamation.

Cons:

- Controlling the deposition strategy to optimize the blending of the coarse and fine waste feeds is challenging.
- It is only really economic where the two feeds can be pumped together or blended for in-pit storage.
- The resulting mix would not be pumpable.

Stage of technology: Applied research, but discontinued.

Knowledge gaps

- Quantification of mixing proportions depending on the material properties and how to obtain adequate mixing.
- Evaluate methods of transportation of the resulting mix.

Relative Cost:

Low

Comments:

References: 7, 39, 45, 46, 72, 102, 103, 104, 123, 127, 131

28. Mixing MFT with other overburden

Description:

Mixing of glacial materials (tills, clays, sands) and MFT to form a semi-solid mixture suitable for storage in polders.

Pros:

- More abundant overburden material to mix with MFT;
- Similar to the mixing MFT with Clearwater overburden, but the glacial materials doesn't contain bentonite.

Cons:

- Controlling the deposition strategy to optimize the blending of the coarse and fine waste feeds is challenging.
- It is only really economic where the two feeds can be pumped together or blended for in-pit storage.
- The resulting mix would not be pumpable.
- Less capacity to uptake water from MFT than Kc.

Stage of technology: Basic research and Applied research.

Knowledge gaps

- Quantification of mixing proportions depending on the material properties and how to obtain adequate mixing.
- Evaluate methods of transportation of the resulting mix.

Relative Cost:

Low

Comments:

References: 7, 39, 102, 103, 123, 127, 131

29. Mixing MFT with reclamation material

Description:

This technology consists of mixing MFT with peat moss to form a semi-solid mixture suitable for early reclamation.

Pros:

- Address legacy MFT.
- Surface material will be ready for reclamation.
- Reduces need for secondary reclamation material.

Cons:

- Toxics compounds in MFT may inhibit plant growth.
- Not proven technology.
- Limited availability of reclamation material.
- Expensive and likely unable to produce commercial forest.

Stage of technology: Basic research, but discontinued.

Knowledge gaps

- Quantification of mixing proportions depending on the material properties.

Relative Cost:

Low

Comments:

References: 31, 92, 93, 125, 142

30. Mixing MFT with coke	
Description:	This technology consists of mixing MFT/CT with coke from the bitumen refining process. Although some of the coke is used as fuel in the processing plants, the remainder is stored for use as a future energy source
Pros:	<ul style="list-style-type: none"> Mix will probably improve consolidation
Cons:	<ul style="list-style-type: none"> Toxics compounds (nickel, vanadium and molybdenum) in coke may bioaccumulate in plants inhibiting their growth. Coke, a source of energy, can be lost in a deposit or difficult to obtain if later required. Benefits are unclear
Stage of technology:	Basic research.
Knowledge gaps	<ul style="list-style-type: none"> Quantification of mixing proportions depending on the material properties. Understanding consolidation behaviour. Understanding depositional behaviour (i.e. segregation). Assessment of toxicity in different plant species.
Relative Cost:	Low
Comments:	
References:	8, 50

31. Mixing thickened tailings with sand

Description:

Mixing of thickened tailings and sand to form a non-segregating mix suitable for poldering.

Pros:

- The mixture has a high solids content and it may be stacked at a significant slope.
- Address new fines.
- May not require containment.
- The high fines/high solids mix will have a high viscosity which will result in formation of a non-segregating system.
- The internal surcharge of sand will raise the effective stress on the clay and promote self-weight consolidation.

Cons:

- Not proven technology.
- Improper application of this technique may result in the creation of reclaimed landforms of dubious environmental and economic value, particularly because of the presence of sodic clays and bituminous residues in oil sands tailings.

Stage of technology: Basic research and applied research.

Knowledge gaps

- Deeper insight into the geotechnical properties of thickened tailings/sand mixes would assist full field-scale planning tests which are extremely expensive.
- Strength and consolidation behaviour of various mixtures of sand and thickened tailings are not known.
- Evaluate liquefaction potential.

Relative Cost:

High upfront and operational costs.

Comments:

Need to determine viability of the thickening process.

References: 5, 6, 7, 24, 26, 27, 44, 65, 75, 112

32. MFT water capped lake

Description:

Permanently storing MFT under a water cap forming a lake which ultimately become a biologically active and self-sustaining functional ecosystem.

Pros:

- Low cost
- Reduction of concentration of chemicals through natural microbial processes.
- Self-sustaining aquatic ecosystem.
- Geologic containment for fluid tailings where stored below original ground.

Cons:

- Cannot be located where the body will recharge groundwater that may ultimately contact sensitive receptors.
- Biological activity in the fluid tailings may emit considerable gas which may result in mixing fluid tailings with overlying water.
- Regulators have not yet approved permanent storage of MFT under a water cap. Instead they have advocated for a solid trafficable landscape (68).

Stage of technology

Applied research and demonstration.

Knowledge gaps

- Uncertainties remain regarding function and success including water quality and toxicity, sustainability and liability.
- Accurate quantification of methane release from biodegradation needs to be addressed.
- Understand how gas production impacts long term water quality.

Relative Cost:

Low

Comments:

This technology is currently being evaluated at Syncrude.

References: 14, 15, 39, 49, 51, 62, 68, 69, 73, 74, 88, 106, 107, 112, 118, 127

33. Pit lake

Description:

Also known as End Pit Lake, it is an engineered water body located below grade in oil sands post-mining pits. The pit lake will ultimately become a biologically active and self-sustaining functional ecosystem.

Pros:

- Low cost
- Reduction of concentration of chemicals through natural microbial processes.
- Self-sustaining aquatic ecosystem.
- Geologic containment for fluid tailings where stored below original ground.

Cons:

- Cannot be located where the body will recharge groundwater that may ultimately contact sensitive receptors.
- Biological activity in the fluid tailings may emit considerable gas which may result in mixing fluid tailings with overlying water.
- Regulators have not yet approved permanent storage of MFT under a water cap. Instead they have advocated for a solid trafficable landscape (68).

Stage of technology: Applied research and demonstration.

Knowledge gaps

- Uncertainties remain regarding function and success including water quality and toxicity, sustainability and liability.
- Accurate quantification of methane release from biodegradation needs to be addressed.
- Understand how gas production impacts long term water quality.

Relative Cost:

Low

Comments:

They are an integral component in the management, operation, and final reclamation landscape of oil sands development. The purpose of EPL is to provide a sustainable landscape feature and final remediation solution for process-affected waters. Through EPL, the environmental impacts of mine operations on aquatic ecosystems should be minimized.

A decision must be made regarding what flood event the EPL will be designed for.

References: 14, 15, 30, 39, 49, 51, 62, 68, 69, 73, 74, 88, 106, 107, 110, 112, 127

34. Store MFT in underground caverns

Description:

Inject MFT in underground caverns or deep wells where future contact with human beings is unlikely.

Pros:

- Prevent additional surface disturbance, less surface tailings storage.
- Tailings can be mixed on the surface with a binder to help minimize groundwater contamination.

Cons:

- High costs, particularly if binders are used.
- Tailings need to be dewatered, increasing costs.
- Requires extra manpower and equipment.
- Requires suitable location and development of caverns.

Stage of technology

Basic research.

Knowledge gaps

- Need to evaluate volumes to be stored, adequate locations and costs.
- Needs to evaluate suitability of this technique to be applied in the oil sands industry.

Relative Cost:

Medium to high upfront cost.

Comments:

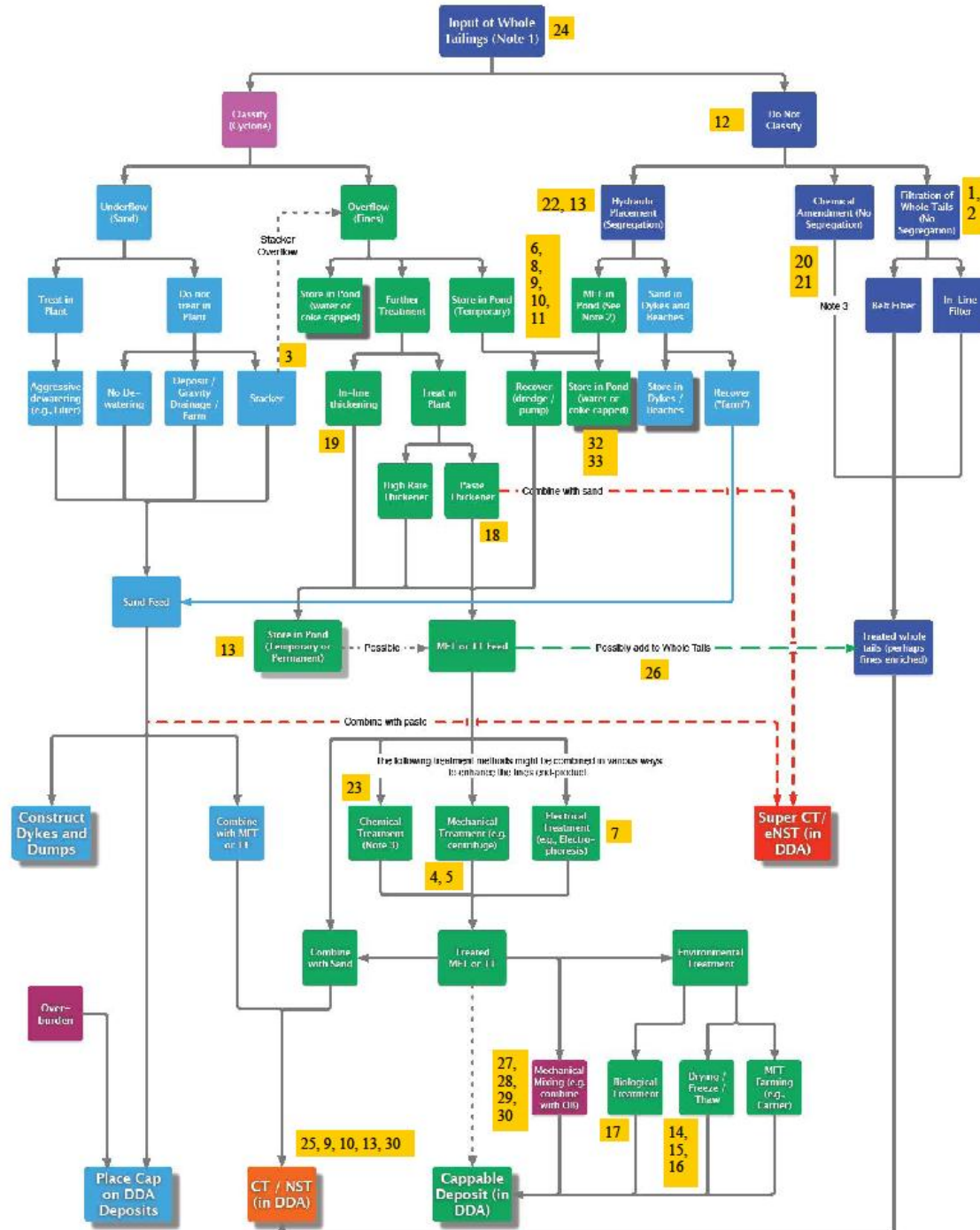
This technology has been suggested, but not seriously researched.

References: None.

APPENDIX 3: Reclaiming Oil Sands Tailings – Technology Roadmap

Diagram 1 - Reclaiming Oil Sands Tailings - A Technology Roadmap
by
J.C. Sobkowicz and N.R. Morgenstern

20090903



To navigate flow chart, proceed down or laterally along paths, (with the exception of dotted lines). At a path intersection, any lateral or downward direction is possible. Dashed line styles are independent paths.

Notes:

1. May or may not blend secondary tailings streams.
2. Includes managing the legacy issue.
3. For example, the addition of inorganic or organic flocculants.

Colour Legend

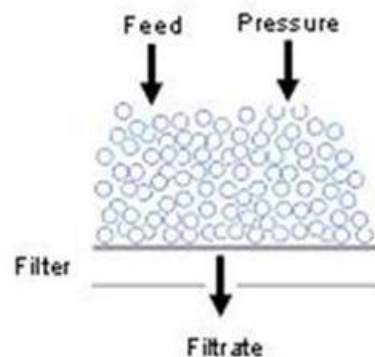


APPENDIX 4: Pictures and Diagrams of Tailings Technologies

The following diagrams and pictures show some of the 34 tailings technologies.

1. Filtered Tailings

Vacuum Filters

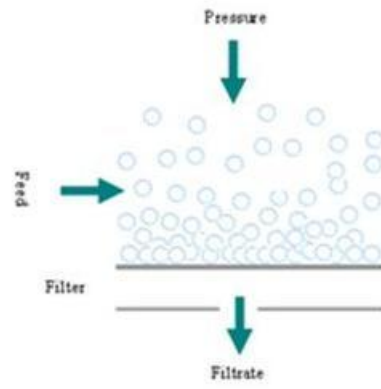


1. Image available from :
http://www.google.ca/imgres?imgurl=http://www.komline.com/images/RDVFKaolin.jpg&imgrefurl=http://www.komline.com/docs/rotary_drum_vacuum_filter.html&usq=__T94c2FpNQW48HPwQz70N2Gu4ewU=&h=400&w=600&sz=39&hl=en&start=1&itbs=1&tbnid=1zJUy019nlJR1M:&tbnh=90&tbnw=135&prev=/images%3Fq%3Dvacuum%2Bfilters%26hl%3Den%26gbv%3D2%26tbs%3Disch:1
2. Image available from:
http://www.google.ca/imgres?imgurl=http://www.desmech.com/wp-content/TFF/Tangential%2520Flow%2520Filtration%2520System%2520Schematic.JPG&imgrefurl=http://www.desmech.com/%3Fp%3D29&usg=__p_u7IYItNUUI99MkXOfHzrMDYI=&h=331&w=525&sz=16&hl=en&start=3&um=1&itbs=1&tbnid=k6qcTZp3Ce6dfM:&tbnh=83&tbnw=132&prev=/images%3Fq%3Dcross%2Bflow%2Bfiltration%26um%3D1%26hl%3Den%26rlz%3D1T4ADFA_enCA358CA358%26tbs%3Disch:1

2. Cross Flow Filtration of Whole Tailings



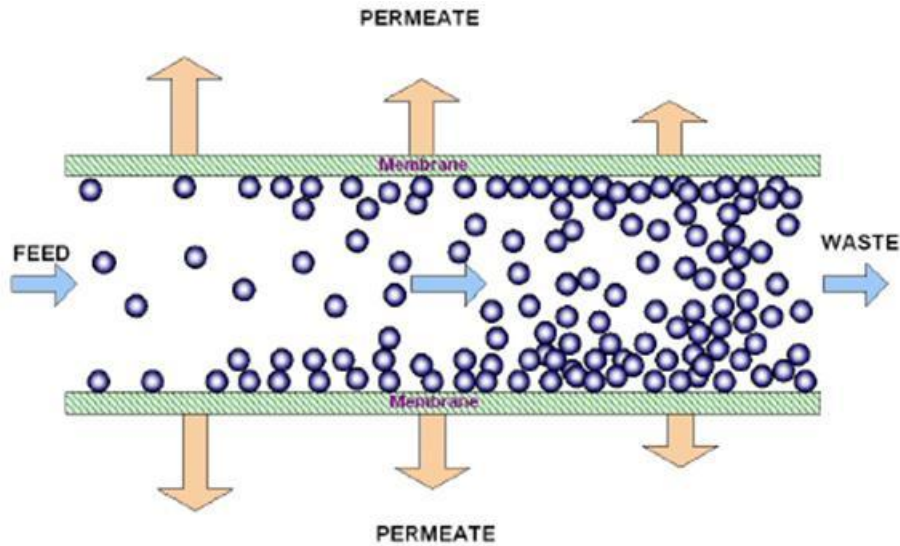
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2



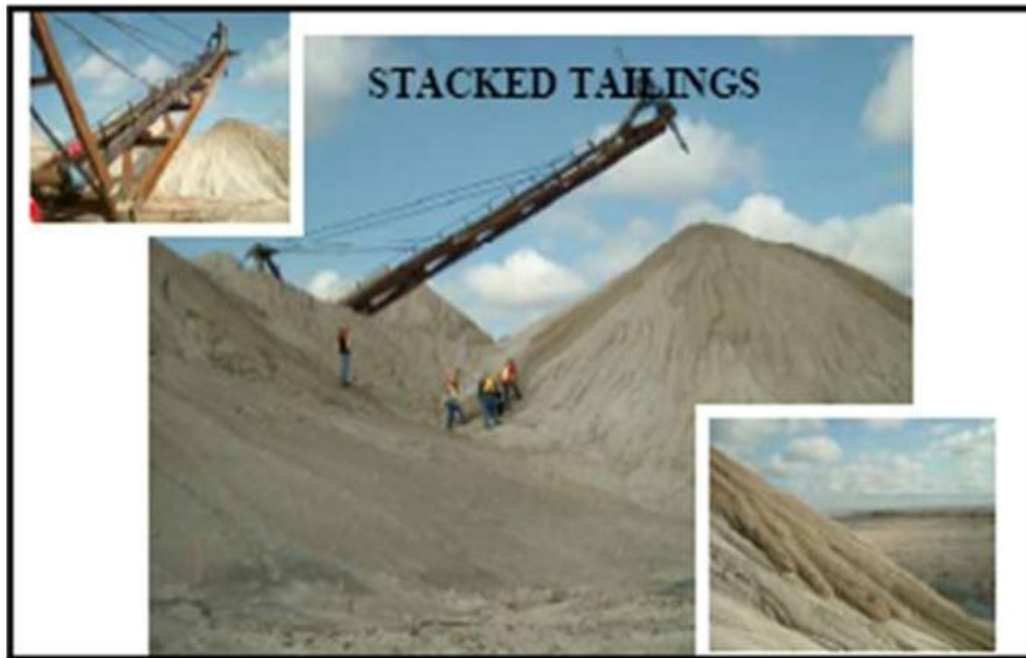
3



4

1. Cross Flow Filtration test conducted at the University of Alberta. Image available from: http://www.google.ca/imgres?imgurl=http://www.ostrf.com/files/downloads/xflow1.JPG&imgrefurl=http://www.ostrf.com/research&usq=cKw-rIDEQODZNhIPY8Rx7r0aHg=&h=375&w=500&sz=42&hl=en&start=1&um=1&itbs=1&tbnid=lkP1VrrMgR9xxM:&tbnh=98&tbnw=130&prev=/images%3Fq%3Dcross%2Bflow%2Bfiltration%2Bfor%2Btailings%26um%3D1%26hl%3Den%26rlz%3D1T4ADFA_enCA358CA358%26tbs%3Disch:1
2. Image available from: http://www.google.ca/imgres?imgurl=http://www.desmech.com/wp-content/TFF/Tangential%2520Flow%2520Filtration%2520System%2520Schematic.JPG&imgrefurl=http://www.desmech.com/%3Fp%3D29&usq=p_u7IYltNUU199MkKXOfHzrMDYI=&h=331&w=525&sz=16&hl=en&start=3&um=1&itbs=1&tbnid=k6qcTZp3Ce6dfM:&tbnh=83&tbnw=132&prev=/images%3Fq%3Dcross%2Bflow%2Bfiltration%26um%3D1%26hl%3Den%26rlz%3D1T4ADFA_enCA358CA358%26tbs%3Disch:1
3. Image available from: http://en.wikipedia.org/wiki/Cross_flow_filtration
4. Cross flow filtration. Image available from: www.environmental-expert.com

3. Filter Thickened Tailings (Coarse Fraction Only)

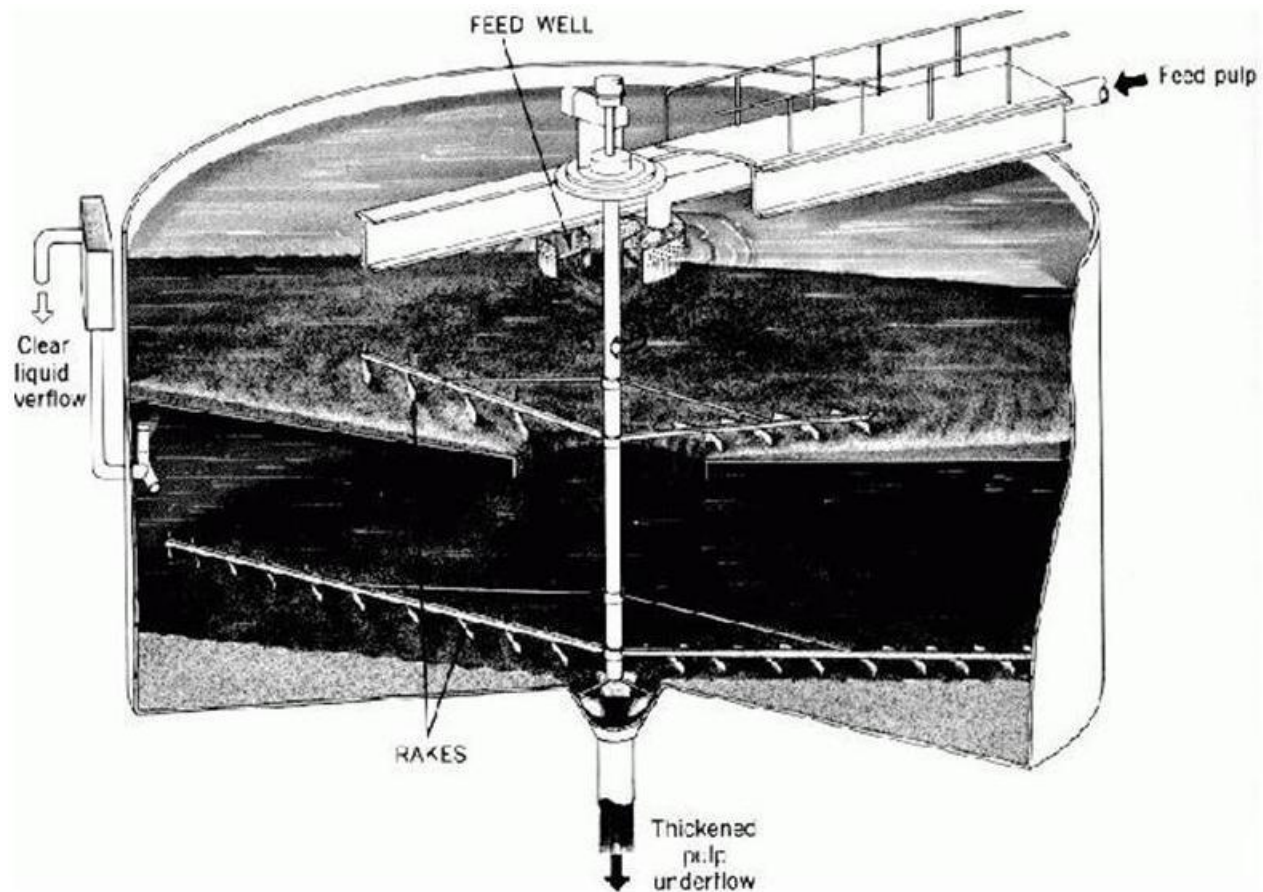


1. Fair, A. The Past, The Present and Future of Tailings at Syncrude. International Oil Sands Tailings Conference Presentation. December 7-10, 2008. Edmonton, Alberta.



2. Images available from: http://www.google.ca/imgres?imgurl=http://www.tailings.info/images/pics/content/bigdrystack.jpg&imgrefurl=http://www.tailings.info/drystack.htm&usg=__wZRW9DWdQO2gkG2kSU0IQiU9_8w=&h=264&w=410&sz=26&hl=en&start=1&um=1&itbs=1&tbnid=7_B5Mg2B_GxmLM:&tbnh=80&tbnw=125&prev=/images%3Fq%3Dfiltration%2Band%2Bdry%2Bstacking%2Bof%2Btailings%26um%3D1%26hl%3Den%26sa%3DN%26rlz%3D1T4ADFA_enCA358CA358%26tbs%3Disch:1

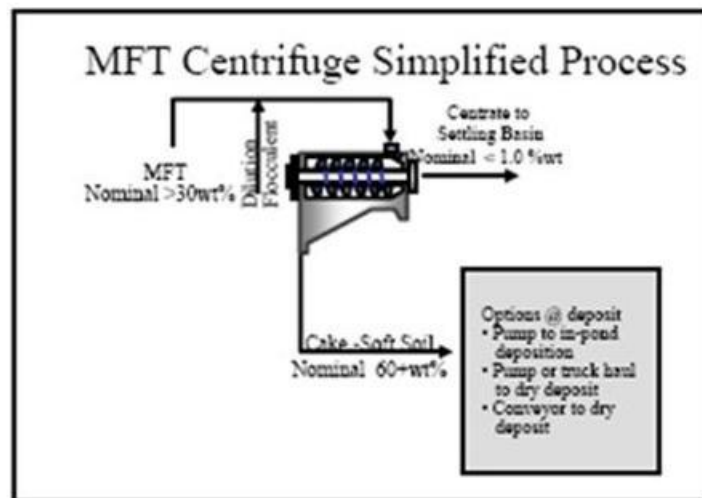
4. Filter Thickened Tailings (Fines Slurry)



Comment: In this diagram the feed would be a fines slurry (MFT) that first will be subject to a thickening process and then the thickened underflow will be subject to a filtration process.

Image available from: <http://users.vianet.ca/dano/thicknr.jpg>

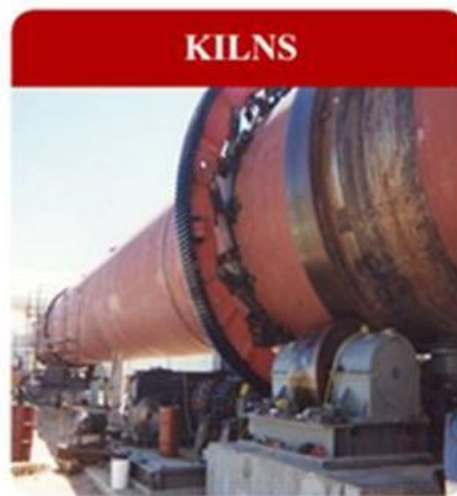
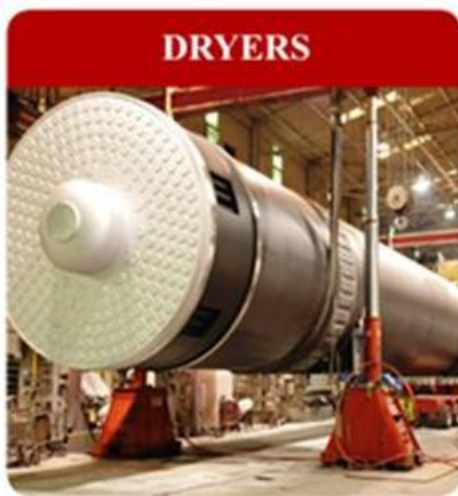
5. Centrifuge



Images available from:

Fair, A. The Past, The Present and Future of Tailings at Syncrude. International Oil Sands Tailings Conference Presentation. December 7-10, 2008. Edmonton, Alberta.

6. Thermal Drying MFT

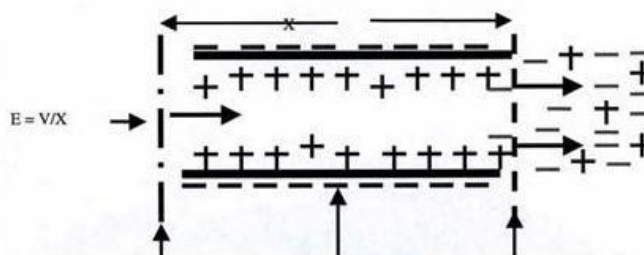


Images available from the Industrial Kiln and Dryer Group TM:

http://www.google.ca/imgres?imgurl=http://www.industrialkiln.com/images/raluca-images/kilns_sm.jpg&imgrefurl=http://www.industrialkiln.com/&usg=__EKLxqzRxs8sV9IIHEhukE_fVxgo=&h=214&w=200&sz=38&hl=en&start=19&itbs=1&tbnid=xn3Zog8lsQ6g9M:&tbnh=106&tbnw=99&prev=/images%3Fq%3Dindustrial%2Bkiln%26hl%3Den%26gbv%3D2%26tbs%3Disch:1

7. Electrical Treatment

Anode (+) Charged particle
capillary wall Cathode (-)
Electroosmotic flow of solution
containing ions through
a capillary of charged particle
walls due to electric potential
difference
 V applied between 2 electrodes at
a distance X .



“For an effective electrokinetic dewatering, both electroosmosis and electrophoresis may be coupled with conductive, interfacial chemistry, particle interactions and pulp network structure. To date however, due to paucity of combined knowledge and understanding of colloid "engineering" and electroosmosis/electrophoresis, the optimization of the underlying and inter-linked processes for maximum dewaterability has not as yet been fully achieved.”

Text and images available from the Ian Wark Research Institute:

http://www.google.ca/imgres?imgurl=http://www.unisa.edu.au/iwri/futurestudents/honsprojects/hondewater.jpg&imgrefurl=http://www.unisa.edu.au/iwri/futurestudents/honsprojects/electrokineticdewatering.asp&usg=__e7CM8hi7ctsU2jD0-tunaQZwltA=&h=288&w=756&sz=19&hl=en&start=8&um=1&itbs=1&tbnid=vLRykkhuVOjToM:&tbnh=54

8. Blast Density



Images available from:

http://www.google.ca/imgres?imgurl=http://www.gaiiacontractors.com/_english/pict/4_1_1.jpg&imgrefurl=http://www.gaiiacontractors.com/_english/4_applications_01.html&usg=__qBHOqgO4QDoChr-KpErt6B2ssUo=&h=220&w=280&sz=14&hl=en&start=4&um=1&itbs=1&tbnid=ILtNmLEUL9Xy4M:&tbnh=90&tbnw=114&prev=/images%3Fq%3Dblast%2Bdensification%26um%3D1%26hl%3Den%26rlz%3D1T4ADFA_enCA358CA358%26tbs%3Disch:1

9. Wick Drains

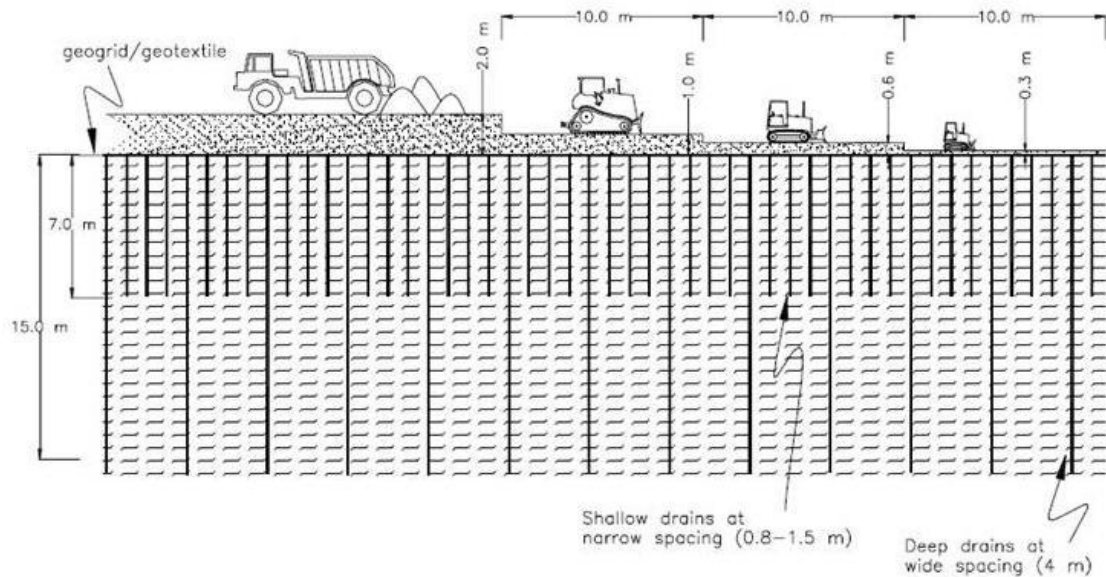


1. Image available from:
http://www.google.ca/imgres?imgurl=http://www.geomembranes.com/productPages/Floodway1.jpg&imgrefurl=http://www.enviroliner6000.com/index_resources.cfm%3FcopyID%3D91%26ID%3Dgeo%26type%3Dcase&usq=__jW3iC3Nku8Y17ZIFC4g67bKKP8U=&h=870&w=570&sz=175&hl=en&start=3&um=1&itbs=1&tbnid=PeYO30NRCBN5eM:&tbnh=145&tbnw=95&prev=/images%3Fq%3Dwick%2Bdrains%26um%3D1%26hl%3Den%26client%3Dfirefox-a%26sa%3DG%26rls%3Dorg.mozilla:en-US:official%26channel%3Ds%26tbs%3Disch:1
2. Image available from :
http://www.google.ca/imgres?imgurl=http://www.layfieldgeosynthetics.com/Content_Files/Images/Product/wick-3.jpg&imgrefurl=http://www.layfieldgeosynthetics.com/pages/Products/Drainage.aspx%3Fid%3D3123&usq=__i5imD1CW0e_aRwGBIsq4LAVqsn=&h=288&w=432&sz=33&hl=en&start=2&um=1&itbs=1&tbnid=INs29oDnKkG9iM:&tbnh=84&tbnw=126&prev=/images%3Fq%3Dwick%2Bdrains%26um%3D1%26hl%3Den%26client%3Dfirefox-a%26sa%3DG%26rls%3Dorg.mozilla:en-US:official%26channel%3Ds%26tbs%3Disch:1

10. Surcharge Loading



1



2

1. Image available from: http://www.marathon.com/content/inline-images/marathon_com/news/features/spotlight_series/moc_spot_WOS_sands_notext.jpg.JPG
2. Soil cover (surcharge loading). Schematic illustration of thin-layer placement showing shallow and deep wick drains and geogrid reinforcement. Source: Roberson GeoConsultans Inc website, <http://www.robertsongeoconsultants.com/publications/wismut99.pdf>

11. CT under MFT - No images available.

12. Increase Tailings Density - No images available.

13. Sedimentation/Self-weight Consolidation - No images available.

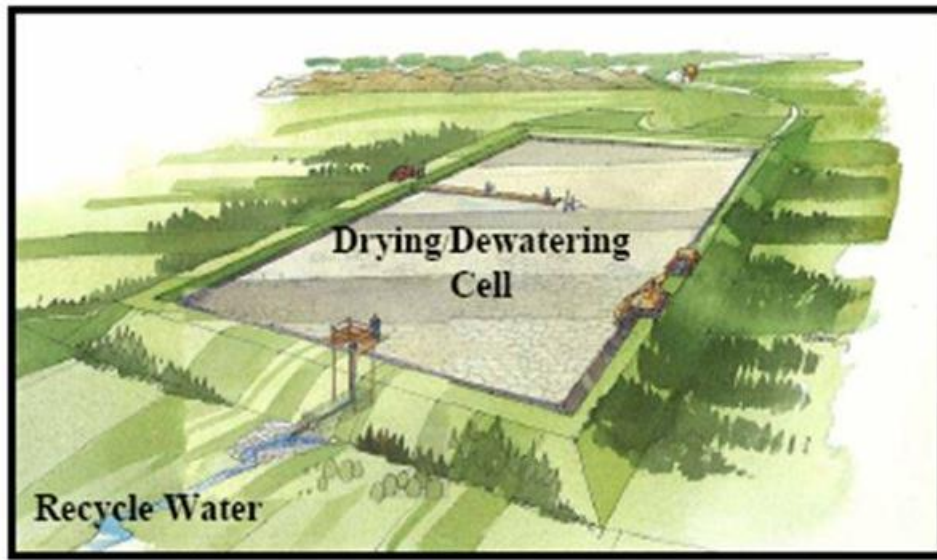
14. Evaporation/Drying



Image of Suncor Energy Inc. dried MFT surface available from:

http://www.google.ca/imgres?imgurl=http://beta.images.theglobeandmail.com/archive/00393/r-cover-tailing1_393183artw.jpg&imgrefurl=http://www.theglobeandmail.com/report-on-business/industry-news/energy-and-resources/battle-for-the-oil-sands/article1406051/&usq=_aLKONSPx9hWCShz_64f2mGNRuyo=&h=340&w=600&sz=102&hl=en&start=1&um=1&itbs=1&tbnid=rycaBu_-_-A6jkM:&tbnh=77&tbnw=135&prev=/images%3Fq%3Ddry%2Btailings%2Bsuncor%26um%3D1%26hl%3Den%26sa%3DN%26rlz%3D1T4ADFA_enCA358CA358%26tbs%3Disch:1

15. Accelerated Dewatering



Images available from: Fair, A. The Past, The Present and Future of Tailings at Syncrude. International Oil Sands Tailings Conference Presentation. December 7-10, 2008. Edmonton, Alberta.

16. Freeze/Thaw - No images available.

17. Biological/Plan Dewatering (Evapotranspiration)

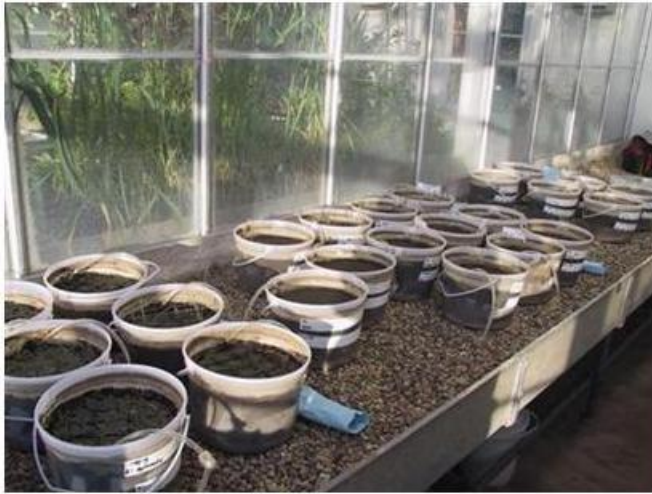


Image available from:

http://www.google.ca/imgres?imgurl=http://www.ostrf.com/files/downloads/xflow1.JPG&imgrefurl=http://www.ostrf.com/research&u sg=__cKw-rlDEQODZNhIPY8Rx7r0aHg=&h=375&w=500&sz=42&hl=en&start=1&um=1&itbs=1&tbnid=lkP1VrrMqR9xxM:&tbnh=98&tbnw=130&prev=/images%3Fq%3Dcross%2Bflow%2Bfiltration%2Bfor%2Btailings%26um%3D1%26hl%3Den%26rlz%3D1T4ADFA_enCA358CA358%26tbs%3Disch:1

18. Thickening Process



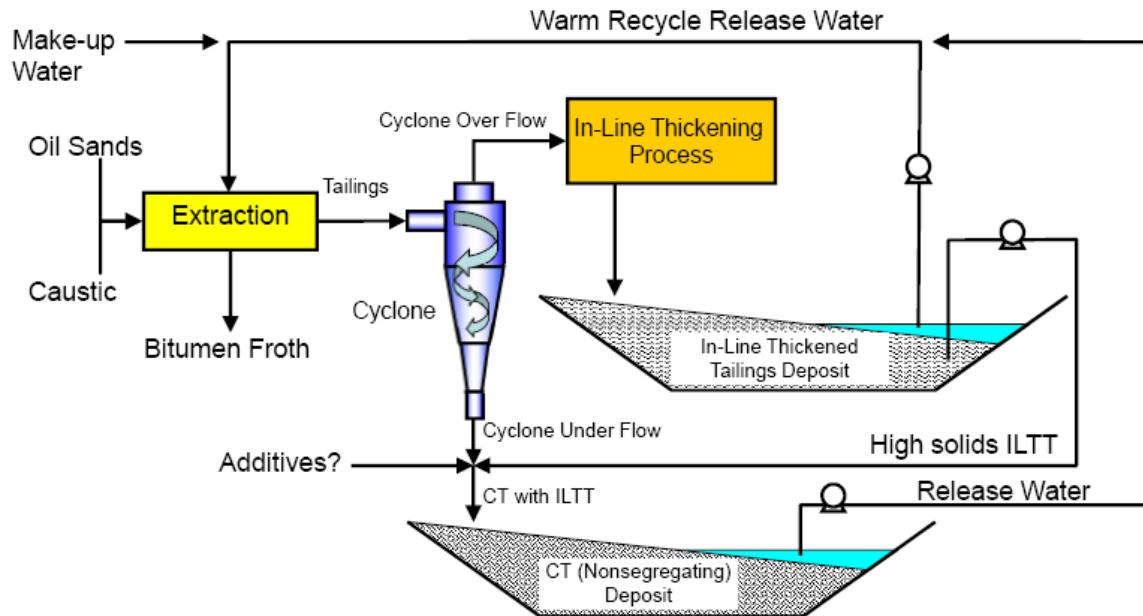
1. Image available from:

http://www.google.ca/imgres?imgurl=http://www.flsmidthminerals.com/NR/rdonlyres/D9D0C568-3786-40E4-8679-5D390A8AC49A/32239/ConventionalThickeners.jpg&imgrefurl=http://www.flsmidthminerals.com/Products/Sedimentation/Clarifiers%2Band%2BThickeners/Clarifiers%2Band%2BThickeners.htm&usq=__ytiwkoWcSLve1CZxdnLv3Yjb824=&h=328&w=414&sz=41&hl=en&start=16&um=1&itbs=1&tbnid=FBYPKTKHOjcSiM:&tbnh=99&tbnw=125&prev=/images%3Fq%3Dthickening%2Btailings%2Btreatment%2B%252B%2Bbrakes%26um%3D1%26hl%3Den%26sa%3DN%26rlz%3D1T4ADFA_enCA358CA358%26tbs%3Disch:1

2. Source: Matthews, J. Oil Sands Tailings Management A Review of Status Quo and Opportunities for the Future. In Oilsand Symposium, May 3-5, 2004. Accessed online May 2010.

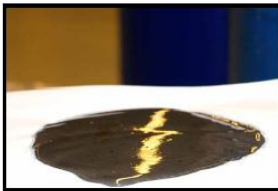
19. In-line Thickening of Fines (ILTT)

In-Line Thickening Process

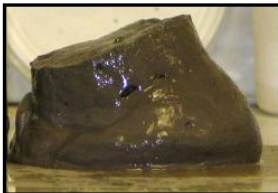


1

ILTT samples



MFT ~32% solids content



ILTT~30% solids content



ILTT ~50% solids content

2

- Image available from:
http://ostrfdownload.civil.ualberta.ca/Tailings%20and%20Mine%20Waste%202009/Oil%20Sands%20Tailings%202/3_geotechnical%20characteristics%20of%20laboratory%20in%20line%20thickened%20oil%20sands%20tailings_Jeeravipoolvarn%20et%20al.pdf
- Image available from:
http://ostrfdownload.civil.ualberta.ca/International%20Oil%20Sands%20Tailings%20Conference%202008/IOTC%20Dec%209%20Presentations/silawat_J.pdf

20. Whole Tailings Coagulation - No images available.

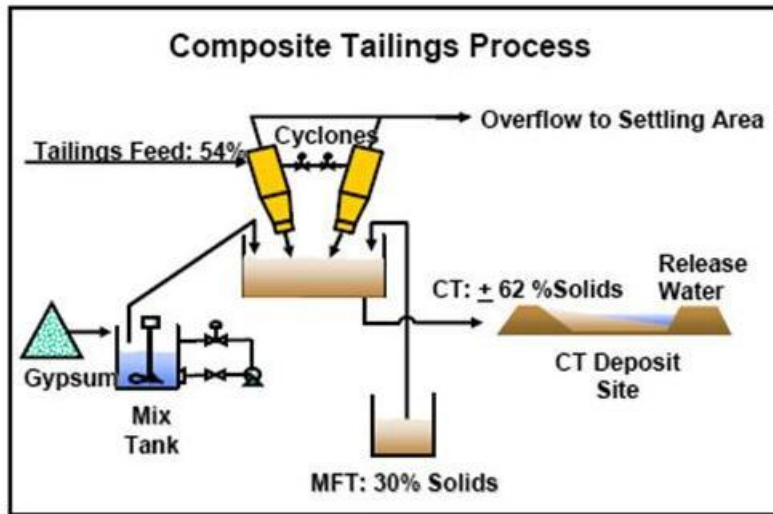
21. Whole Tailings Flocculation - No images available.

22. In-situ Biological Treatment of MFT/TFT - No images available.

23. In-situ Chemical Treatment of MFT - No images available.

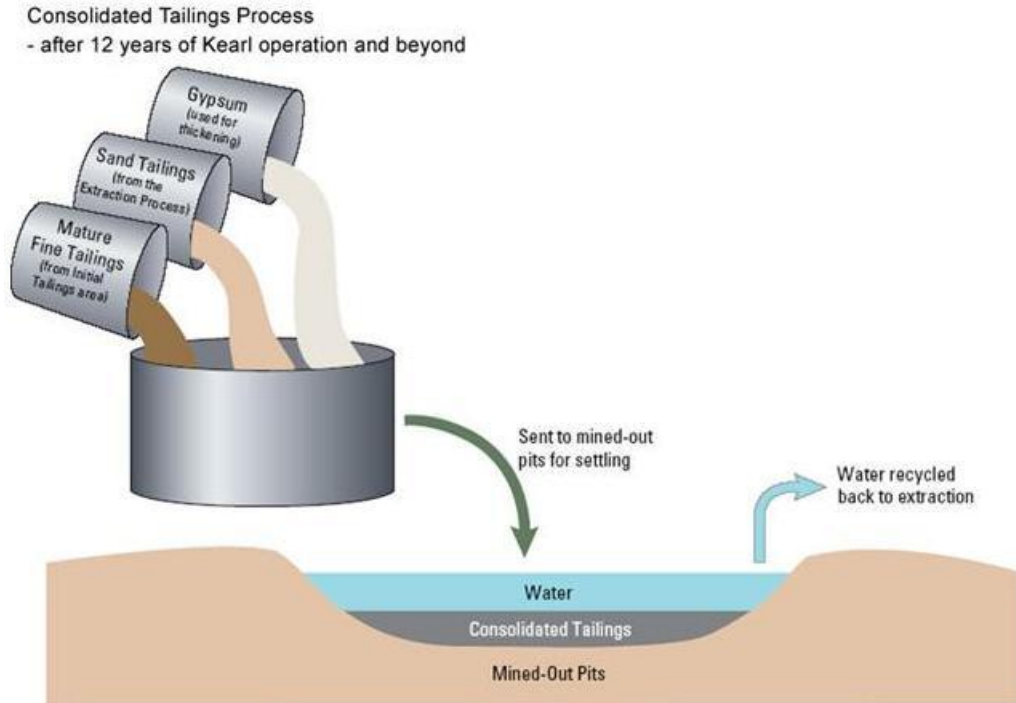
24. Reduce Dispersion of Fines in Process - No images available.

25. Composite/Consolidated (CT) Tailings



1

- Image available from:
Fair, A. The Past, The Present and Future of Tailings at Syncrude. International Oil Sands Tailings Conference Presentation. December 7-10, 2008. Edmonton, Alberta.



2

- Image available from:
http://www.imperialoil.ca/Canada-English/Images/ThisIs/im_kearl_tailings_2_large.jpg

26. MFT Spiked Tailings - No images available.

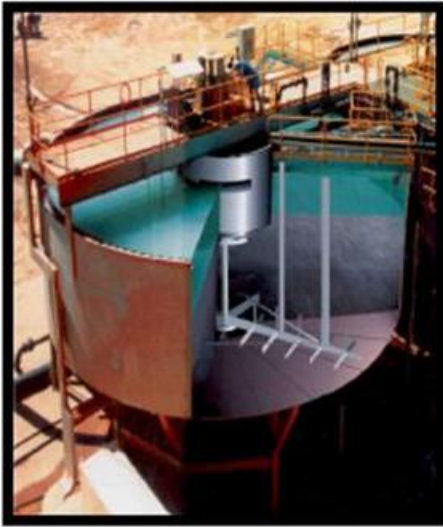
27. MFT with Clearwater Overburden - No images available.

28. MFT with Other Overburden - No images available.

29. MFT with Reclamation Material - No images available.

30. MFT with Coke - No images available.

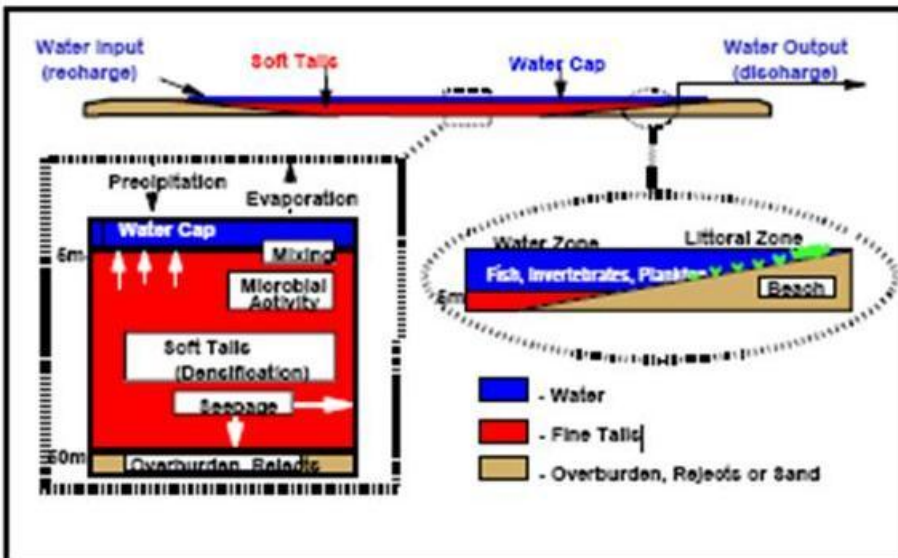
31. Thickened Tailings with Sand



Images available from:

Fair, A. The Past, The Present and Future of Tailings at Syncrude. International Oil Sands Tailings Conference Presentation. December 7-10, 2008. Edmonton, Alberta.

32. MFT Water Capped Lake



Images available from:

Fair, A. The Past, The Present and Future of Tailings at Syncrude. International Oil Sands Tailings Conference Presentation. December 7-10, 2008. Edmonton, Alberta.

33. Pit Lake

“The first geomembrane-lined mine pit backfilled with conventional tailings was the El Valle mine pit located in Asturias in northern Spain. The gold mine pit was depleted of ore adjacent to other ongoing nearby active mine pit operations by 2003.”



Images and text available from:

http://www.google.ca/imgres?imgurl=http://geosyntheticsmagazine.com/repository/2/6960/full_0410_f1_4.jpg&imgrefurl=http://geosyntheticsmagazine.com/articles/0410_f1_backfill.html&usg=__rn5O1K1_VU8liiOatF2t0XiiNJ0=&h=531&w=720&sz=256&hl=en&start=8&um=1&itbs=1&tbnid=VE_TGAoXto06zM:&tbnh=103&tbnw=140&prev=/images%3Fq%3Dtailings%2Bpit%2Bblakes%26um%3D1%26hl%3Den%26rlz%3D1T4ADFA_enCA358CA358%26tbs%3Disch:1

34. Store MFT in Underground Caverns - No images available.