OIL SANDS TAILINGS
TECHNOLOGY DEPLOYMENT ROADMAP

PROJECT REPORT – VOLUME 2
COMPONENT 1 RESULTS

Report
to
Alberta Innovates – Energy
and Environment Solutions

Date: June 22, 2012

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June 22, 2012

Rick Nelson
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Dear Rick,

**Re: Oil Sands Tailings Roadmap – Project Report – Component 1 Results**

We are pleased to provide the attached report “Oil Sands Tailings Technology Deployment RoadmapProject Report - Component 1 Results.”

Yours sincerely,

Per:

Gordon McKenna, PhD, PEng, PGeol
Senior Geotechnical Engineer
BGC Engineering Inc

Richard Dawson, PhD, PEng, PGeol
Senior Vice President
Norwest Corporation
Alberta Innovates – Energy and Environment Solutions (AI-EES), in collaboration with the recently formed Oil Sands Tailings Consortium (OSTC), contracted the Consortium of Oil Sands Tailings Management Consultants (CTMC) to prepare a technology deployment roadmap for “end to end” solutions for oil sands tailings. This report presents the findings and recommendations from Component 1 of the team, charged with gathering available information on oil sands tailings, summarizing the current state of knowledge and practice, and identifying and describing tailings management technologies used in the oil sands and around the world. The other component groups will use the information from this report in their assessment and preparation of the roadmap.

Component 1 identified 549 technologies through a review of commercial practice in the oil sands, interviews with OSTC and CTMC members, a literature review, discussions with vendors, and a newspaper advertisement. With refinement, these were reduced to 101 unique technologies. We classified the information in two main ways – the stage of development for each technology and its position in the mining life cycle. The former was divided into research, development and commercial, using the specific definitions given in this report. The latter was divided into the following categories: mining, extraction, tailings processing, tailings deposition, reclamation, and water treatment. We further identified technologies that were used commercially elsewhere but not in the oil sands (which turn out to be few), and those which were variations or enhancements of the base 101 technologies (the enhancements were mostly chemical aids for tailings processing).

We’ve identified just a few technologies in the mining category that can be used to reduce the amount of fines reporting to tailings. Similarly, there are only a few opportunities in water based extraction to influence tailings behaviour in a meaningful way, but other, non-water based methods may provide an opportunity to avoid creating tailings slurries, if some of the environmental and economic hurdles can be overcome. Most of the technologies considered in this study were in the tailings processing and tailings capping and deposition categories. There were also a number of reclamation and water treatment technologies that can be applied to a variety of tailings situations.

It remains critical that the process affected water chemistry be adjusted or maintained such that it does not adversely impact bitumen recovery, and can be dealt with safely in the reclaimed landscape and made suitable for eventual discharge to the environment (that is, that the total dissolved solids, pH, and chronic and acute toxicity are kept within favourable limits).

To summarize the state of practice for tailings management, we identified eight main tailings schemes, each composed of seven to ten technologies. In all, there are 21 tailings technologies already in commercial use, many mature, some coming on stream just recently (and may be considered pre-commercial) mostly in response to recent changes in regulations. There is an opportunity to use this framework for a gap analysis, identifying where existing commercial
technologies could be improved, replaced, or augmented by other technologies to create tailings that better meet tailings management goals. We’ve also made specific conclusions and recommendations regarding several aspects of commercial operations, most notably to revisit the processing of froth tailings to reduce its potential environmental impacts.

To provide a summary of tailings development, we compiled a table of tailings pilots and prototypes conducted over the past 30 years. Many of these pilots have led to commercial implementation. We’ve recommended revisiting the results of the other pilots to see if there are any technologies that should be reconsidered for commercialization, in the light of the current regulations and economic environment.

For the technologies at the research stage, the supporting data varies from excellent to nearly nonexistent. We’ve recommended developing a standard suite of laboratory tests to put research technologies on a common footing, and reviewing the existing information to see what technologies require further testing and which ones might be candidates for pilots. Furthermore, we’ve recommended that AI-EES and the OSTC develop a formal scanning process to seek out and receive new technologies as they are developed, and to embark on their own research and development (R&D) programs over the next 30 years.

We’ve framed 20 recommendations within the text that are gathered in the final chapter of the report.
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1. INTRODUCTION

Oil sands mines near Fort McMurray, Alberta, Canada (Figure 1-1) produce very large quantities of solid and fluid tailings. Mining, and the corresponding tailings production, has been ongoing for over 40 years and is expected to continue, at increasing rates, in the coming decades. There are ongoing concerns about the geotechnical risks, environmental risks, and long-term liability related to tailings production. In particular, there are concerns related to production, storage, and reclamation of fluid tailings. This report documents the commercial state of practice for tailings management, and describes various mining, extraction, tailings, deposition, reclamation, and water treatment technologies in all stages of development based on a world-wide technology search. This report provides a summary of our findings.

Figure 1-1: Location Map (reproduced from ERCB/AGS)
1.1 Background

Oil sands tailings (various mixtures of sand, fines, process affected water, and residual bitumen\(^1\)), are produced by water-based bitumen extraction processes, and are stored in the landscape behind dams and in mined out pits. Numerous technologies are employed commercially to manage oil sands tailings. Release water from tailings is recycled back to the extraction plant and the tailings areas are reclaimed progressively. Most of the existing reclamation is on the downstream faces of dams (terrestrial reclamation to boreal forest). Recently, the first tailings pond was reclaimed (Suncor Pond 1) to a mixture of terrestrial and wetland landforms.

Each mine has a closure and reclamation plan approved by Alberta Environment under the Environmental Protection and Enhancement Act (EPEA). These plans indicate the final disposition of tailings in the closure landscape, the stabilization and reclamation methods that have and will be employed, the reclamation schedule, and the suitability of the reclaimed landscape for specific approved end land uses. Under EPEA, the mines are required to create self-sustaining reclaimed landscapes that have equivalent capability for land uses typical of the boreal forest. Most of the focus is on creating landscapes that attempt to match the boreal forest ecosystems that provide wildlife habitat and First Nations traditional land uses. It is understood that under this regulatory framework there can be no dams in the final landscapes, and all mining landforms must be reclaimed to acceptable quality surface water discharge with minimal intervention. The need for reclamation to boreal forest ecosystems with good landscape performance dominates the design of the closure landscape and controls tailings management and technology selection.

First Nations and government regulators have long expressed ongoing concern with tailings management in the oil sands. In recent years, issues related to oil sands tailings have gained international attention and are regularly featured in the Canadian and international media. Specific concerns related to oil sands tailings are being more clearly articulated. Table 1-1 describes concerns (which relate to oil sands development, but are also broadly applicable to tailings) and is adapted from the recent Royal Society of Canada’s report (2010).

\(^1\) See Appendix A for a glossary of oil sands tailings terms
Table 1-1: Oil Sands and Tailings Environmental Concerns

<table>
<thead>
<tr>
<th>Concerns raised by Royal Society of Canada (2010)</th>
<th>Suggested potential concerns related more specially to tailings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feasibility of reclamation and adequacy of financial security.</td>
<td>Concern about technical and financial aspects of reclaimability of tailings ponds (plateaus), fluid tailings, and dyke slopes.</td>
</tr>
<tr>
<td>Impacts of oil sands contaminants on downstream residents.</td>
<td>Human health aspects of recycle water.</td>
</tr>
<tr>
<td>Impacts on population health in Wood Buffalo.</td>
<td>Dusting? Water quality? Odours?</td>
</tr>
<tr>
<td>Impacts on regional water supply.</td>
<td>Fresh water import, efficient use of water / water recycle, water discharge back to the Athabasca River.</td>
</tr>
<tr>
<td>Impacts on regional water quality and groundwater quality.</td>
<td>Concern about tailings water quality, water treatment, surface future water discharge, and groundwater / seepage discharge.</td>
</tr>
<tr>
<td>Tailings pond operation and reclamation.</td>
<td>Concern about dam safety, speed of reclamation.</td>
</tr>
<tr>
<td>Impacts on ambient air quality.</td>
<td>Dusting? Odours / fugitive emissions?</td>
</tr>
<tr>
<td>Environmental regulatory performance.</td>
<td>Monitoring and reporting of tailings management and reclamation.</td>
</tr>
</tbody>
</table>

Tailings management in the oil sands has evolved over the 40 years since mining started at the current Suncor lease (formerly Great Canadian Oil Sands Project). There are three overlapping periods of tailings technology development:

- **1960s through 1980s**: Focus on waste management (materials handling and geotechnical stability). Numerous large dams were constructed from tailings to hold fluid fine tailings, space was left in mined out pits for long-term storage of fluid tailings, focus was on constructability, safety, and cost. Syncrude initiated work on water-capped lakes in this period.

- **1990s through 2000s**: Focus on creating solid tailings landscapes capable of supporting terrestrial reclamation and land uses. Research, development, and implementation of sand-capped composite tailings, ongoing research and development of water-capped MFT end pit lakes.

- **2010s**: Focus on meeting new regulatory goals to reduce production and legacy volumes of fluid tailings, speeding reclamation. Rapid research, development, and implementation of high-fines soft tailings treatment technologies.
Responding to public, First Nations, and regulatory concerns regarding the ever growing volumes of fluid tailings, the Energy Resources Conservation Board (ERCB) issued Directive 074 in 2009 that required mines to reduce the generation of fluid fine tailings, manage existing inventories of fluid fine tailings, and create deposits with prescribed solid-like shear strengths during the same year of deposition. This directive, and the proposed Tailings Management Framework, has generated a new focus in oil sands tailings management as described above.

Recognizing the need and benefit for better collaboration on tailings technology development and tailings management, the oil sands industry formed the Oil Sands Tailings Consortium (OSTC) in 2010. AI-EES, working in collaboration with the OSTC, retained the CTMC to document the current state of practice for tailings management and assemble technologies for oil sands tailings management from sources around the world. The intent was to evaluate these technologies in order to provide an “End-to End” roadmap for research and development (R&D) on new technologies and for revision of existing technologies to address the concerns of industry, regulators, stakeholders, and First Nations.

From the Project Execution Plan (PEP), the CTMC has four component teams (see also Figure 1-2):

- Component 1: Background, existing conditions and tailings technologies
- Component 2: Screening criteria
- Component 3: Evaluation and selection of options
- Component 4: Develop roadmap

The present report summarizes the results of the Component 1 work on background and existing technologies.
Figure 1-2: Roles for Each CTMC Component Team
1.2 Project Goals and Objectives

The following goals are based on the CTMC Project Execution Plan (2011):

The “Technology Deployment Roadmap and Action Plan for ‘End-To-End’ Solutions for Oil Sand Tailings” (Tailings Roadmap/Action Plan) is an initiative of both the government and industry to support a broader strategy for sustainable management of tailings produced by the oil sands industry. The Tailings Roadmap / Action Plan initiative will provide a framework to government and industry that will:

- Help achieve more timely deployment of the end-to-end tailings technologies, and share the results and knowledge of tailings deployment activities.
- Document the current state of tailings reclamation technology to define technology pathways to reach the end goal.
- Serve as a basis for accessing government and industry funding to accelerate commercial scale demonstration of technology and promote sharing and technology transfer.
- Identify technology options and establish a framework for operators to conduct detailed feasibility studies and deploy technology, and allow regulators to verify the performance during this process.
- Promote a collaborative approach to oil sands tailings technology that expedites technology deployment, reduces environmental impacts beyond the boundaries of the mine lease and enhances public trust.
- Provide a medium for sharing the results and knowledge of effective tailings deployment initiatives.

1.3 Component 1 Scope of Work

The scope of Component 1 is to establish the foundation for the rest of the study by identifying relevant tailings technologies, collecting key information, writing a description (of the technologies) that uses a common basis/language, and documenting the current state of practice.

According to the Project Execution Plan, Component 1 was divided into four tasks:

- **Task 1 Data Gathering:** To seek and assemble electronic copies of available papers, reports, and datasets for a broad range of tailings technologies, document the list of available information and contacts into a spreadsheet database, and communicate this information with a task report that includes the bibliography.

- **Task 2 Summarize Current State of Knowledge:** To summarize the current state of knowledge for oil sands tailings providing a summary of historic work, tailings material properties, and related local climatic conditions.
• **Task 3 Describe Current State of Practice:** To document current tailings management systems, explain how they operate, identify challenges and benefits, and identify the applicable set of lease conditions. This will provide a good understanding of the issues and constraints associated with adopting new tailings technology.

• **Task 4 Identify and Describe all Known Tailings Management Technologies:** To summarize the current state of knowledge of oil sands tailings management technologies, create a spreadsheet database detailing tailings management technologies, and categorize the applicable tailings materials based on categories and the state of technology development.

The Component 1 team has prepared this deliverable to the CTMC Team to achieve these tasks. Component 1 Results Report gives an overview of the state of practice and a summary of the technologies that have been identified for each stage of development. The work resulted in a number of key insights and findings that should be considered in subsequent stages of the roadmap project.

1.4 **Component 1 Project Team**

The Component 1 project team includes involved staff of BGC Engineering, Norwest Corporation, and Thurber Engineering lead by:

- **Gord McKenna**, Ph.D., P.Eng., P.Geol., Senior Geotechnical Engineer, BGC Engineering Inc., Vancouver
- **Richard Dawson**, Ph.D., P.Eng., P.Geol., Senior Vice President and Senior Geotechnical Engineer, Norwest Corporation, Vancouver

And also included:

- **Aaron Sellick**, P.Eng., Senior Mining Engineer, Norwest Corporation, Halifax
- **Andy Jamieson**, EIT, Geotechnical Engineer, BGC Engineering Inc., Vancouver
- **John Sobkowicz**, Ph.D., P.Eng., Principal and Senior Geotechnical Engineer, Thurber Engineering Ltd. Calgary
- **Phil LeSueur**, EIT, Geotechnical Engineer, BGC Engineering Inc., Vancouver, Lead

Additionally, the following contributed their time, energy and insights to the team:

- **Alan Fair**, P.Eng., Executive Director, Geotechnical Engineer, Oil Sands Tailings Consortium, Edmonton
- **Al Hyndman**, P.Eng., Senior Mining Consultant, Magnus Limited / Total E&P Canada, Calgary
- Bill Shaw, P.Eng., Tailings Engineer, WHS Engineering Ltd. / Total E&P Canada, Calgary
- Blair Penner, P.Eng., Senior Process Engineer, Suncor Energy, Fort McMurray
- Rick Sisson, P.Eng., Senior Geotechnical Engineer, Canadian Natural Resources Ltd., Calgary
- Sean Wells, P.Eng., Manager, Tailings Research Engineer, Suncor Energy, Calgary
- Ted Lord, P.Eng., Senior Geotechnical Engineer, ERCB, Calgary

Al Hyndman’s and Bill Shaw’s time was provided by Total E&P Canada, Blair Penner and Sean Well’s time was provided by Suncor, Rick Sisson’s time was provided by CNRL, and Ted Lord’s time was provided by the ERCB. This generously provided support was integral to the success of the project. See Figure 1-3.

The team was co-chaired by Gord McKenna and Richard Dawson. Technical support (mainly in completing technology sheets) was provided by the following BGC staff: Dale Heffernan, Dylan Lee, Joel van Horn, EIT, Elisa Scordo, P.Ag., Sam Cho, Scott Carrier, EIT, and Silawat (Song) Jeeravipoolvarn, Ph.D. Mike Rogers, M.Sc., and Paul Pigeon, P.E., P.Eng. of Golder Associates provided their insight and efforts on the water treatment technologies.

Illustrations are by Derrill Shuttleworth of Gabriola Island, (www.dshuttleworth.com). Photos in the report are courtesy of the oil sands operators and the CTMC.

Recognition is due in particular to Phil LeSueur who managed the master technology list, the hundreds of datasheets, and provided the primary interface with the many third-party vendors who contributed their technology information to the study.
1.5 Layout of this Report

The first two chapters of this report provide background, methods, and the assembled lists of tailings technologies. The next chapters look at the state of practice for oil sands mining, tailings, reclamation, and water treatment (with a focus on how each of these affects tailings), and the state of oil sands development and research. The last chapters provide a summary and recommendations.

1.6 Oil Sands Tailings Glossary

As a basis for communicating technical information in a consistent way, a glossary has been developed to define the terms used throughout the study (Appendix A). The CTMC Glossary is written in narrative form, following the classification system outlined below. It builds on common usage of terms within the industry and is meant to provide a consistent terminology for the CTMC Roadmap. It is focused on local usage rather than defining common equipment or processes elsewhere in the mining industry.

1.7 Technology Stage of Development

Tailings technology development is a continuous process. Industry often brings the technology through various stages of development to reduce the risk and cost of commercial implementation. Technologies move first through a research stage, and some of these technologies then move through a development scale where they are piloted and often
prototyped. The few that are still promising (technologically, economically, and in terms of risk and benefit) are commercialized.

This set of definitions attempts to categorize the technology development steps, to bring a framework to the present roadmap work and to lump together technologies less ambiguously. Table 1-2 provides a broad overview for the typical attributes at different stages of development. For this study the primary distinguishing attribute between the different stages of development is scale. On this basis, a commercialized technology has been trialed at a large field scale as opposed to research technologies, which typically involve bench scale experiments. This classification removes economics as a primary consideration for determining the stage of development of a particular technology, with associated advantages and disadvantages. The definitions are tailings focused, but can be extended to include extraction and water treatment pilots (see Figures 1-4 through 1-8). The three stages of technology development are defined as follows:

- **Research** usually involves a new technology or revisit of existing technology at a bench / laboratory scale, usually a batch process, and is not closely tied to economics (it
usually concentrates on the potential benefits of the technology). The work may apply to a specific technology or may be aimed at gaining a better understanding of fundamental processes. Research focuses on understanding and assessing technologies.

- **“Development”** involves a promising, well-researched technology that has graduated from the research stage and is ready to be tested at field scale, typically at many orders of magnitude greater fluxes than practical in the lab. Development focuses on scale up and performance under continuous operation, and includes environmental and economic assessments. It also aims to identify fatal flaws, provides opportunity to learn how to design, construct, operate and implement technologies, and characterizes the environmental impacts to the degree where the technology can be permitted at a commercial scale. There are two types or scales of development projects:
  - **“Pilots”** typically run on a continuous basis utilizing a slip stream from a commercial line or a small scale reprocessing system (approximately 1 to 10% of proposed commercial fluxes), often conducted under ideal weather / seasonal conditions with well-conditioned and consistent inputs and favourable deposit geometries. It is closely controlled and instrumented, and usually run by expert contract crews and dedicated technical staff. The deposits are small and are turned into temporary or permanent test plots for reclamation.
  - **“Prototypes”** run at commercial scale, but involve a single (tailings) line and may shut down when conditions are poor. The deposits are permanent and reclaimed using commercial scale equipment. They are large enough to gain confidence to move to commercial scale, and are designed to allow optimization of design for commercial implementation, to fit into mining and closure plans, and to receive regulatory approval. The focus is on testing at full scale, developing parameters, optimizing design for commercial operation, and gaining commercial-scale experience for operators.

- **“Commercial”** scale tailings operations run one or more lines at full commercial rates, typically year round (or at least for full seasons). A focus of commercial scale operation is large scale, safe, reliable, cost-effective operation, with continuous improvement.
Figure 1-5: Example of Lab-Scale Tailings Settling Columns

Figure 1-6: Example of a Field Pilot

Figure 1-7: Example of a Prototype Demonstration
Figure 1-8: Example of Commercial Tailings Operation
Table 1-2  Tailings Technology Development Definition Matrix

<table>
<thead>
<tr>
<th>Description</th>
<th>Research</th>
<th>Development</th>
<th>Prototype</th>
<th>Commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usually involves a new technology or revisit of existing technology at a beach / laboratory scale, usually a batch process, and is not closely tied to economics (it usually concentrates on the potential up side of the technology). The work may apply to a specific technology or may be aimed at gaining a better understanding of fundamental processes.</td>
<td>Involves a promising, well-researched technology that has graduated from the research stage and has is ready to be tested at field scale, typically many orders of magnitude greater fluxes than practical in the lab: Development focuses on scale up, performance under continuous operation, and includes environmental and economic assessments. It also aims to identify fatal flaws, provides opportunity to learn how to design, construct, operate and implement technologies and characterizing the environmental impacts to the degree where it can be permitted at commercial scale.</td>
<td>Prototypes run a commercial scale, but involving a single line and may shut down when conditions are poor. The deposits are permanent and reclaimed using commercial scale equipment. They are large enough to gain confidence to move to commercial scale and are designed to allow optimization of design for commercial, to fit into mining and closure plans, receive regulatory approval. The focus is on testing at full scale, developing parameters and optimizing design for commercial operation, and gaining commercial-scale experience for operators.</td>
<td>Commercial scale tailings operating run one or more lines at full commercial rates, typically year round (or at least for full seasons). They have regulatory. To be considered commercial, the technology needs to be fully implemented and running successfully at least one oil sands operation. A focus of commercial scale operation is safe, reliable, cost effective operation, with continuous improvement.</td>
<td></td>
</tr>
<tr>
<td>Focus</td>
<td>Research focuses on understanding and assessing technologies.</td>
<td>Scaling up and testing whether the technology can work under continuous operating conditions, quality of streams, initial costs, information for full scale design, environmental aspects.</td>
<td>Testing at full scale, developing parameters and optimizing design for commercial operation.</td>
<td>Safe, reliable, cost effective operation, continuous improvement.</td>
</tr>
<tr>
<td>Controls and Measurements</td>
<td>Experiments are tightly controlled, often based on just one or two buckets or barrels of ore, tailings, or water. Experiments are often designed so that single variables can be altered (often fines contents, solids contents, or amendment dosages), and replicates can be run.</td>
<td>Pilot scales allow considerable control and measurement of processes and products. Two or three major experiments may be run and there is the opportunity to change conditions part way through each test. Replicates are not usually practical.</td>
<td>Prototypes are usually focused on commercial operations, but allow changes to configuration if the process is not working as intended. Prototypes are often highly instrumented and controlled and may have novel instrumentation.</td>
<td>Limited ability to control feed properties, modest controls and measurements aimed at maintaining critical operating conditions, limited opportunities for experimentation.</td>
</tr>
<tr>
<td>Typical Program Costs</td>
<td>$10 K to $200K/year over one year. Two to five part time technical people.</td>
<td>$500 K to $10 M over one year. A dozen contract operators, technical people, and managers full and part time – staff and contractors are often experts in piloting and prototyping.</td>
<td>$10 M to $50 M over two years. Several dozen contract operators, technical people, and managers full and part time– staff and contractors are often experts in piloting and prototyping.</td>
<td>$500 M to $10 B over 20 years. Up to about 100 operations, technical, management, and support staff full time, many more supporting part time.</td>
</tr>
<tr>
<td>Location</td>
<td>Laboratory</td>
<td>Field</td>
<td>Field / commercial</td>
<td></td>
</tr>
<tr>
<td>Economic Assessment</td>
<td>Preliminary screening level economics.</td>
<td>Economic assessment based on actual mine plans.</td>
<td>Formal internal project assessment, often using a staged-gate approach.</td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td>Usually limited to simple water quality characterization, sometimes greenhouse studies.</td>
<td>Large field scale reclamation, instrumented watershed, and broad commercial-scale reclamation.</td>
<td>Part of the normal mining / environmental / reclamation system.</td>
<td></td>
</tr>
<tr>
<td>Regulatory</td>
<td>Does not usually require regulatory approval. May be mandated and monitored under an EPEA approval condition.</td>
<td>Regulatory notification. Typically includes approval for deposit.</td>
<td>Full regulatory approval required. Will usually require amendment to EPEA operating approval or even public hearing / re-open EIA.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Research</td>
<td>Pilot</td>
<td>Prototype</td>
<td>Commercial</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------</td>
<td>---------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td><strong>Tailings Scales</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deposit volume m^3 (~t)</td>
<td>10^-2 to 10^-1</td>
<td>10^-2 to 10^-1</td>
<td>10^-2 to 10^-1</td>
<td>10^-2 to &gt;10^-1</td>
</tr>
<tr>
<td>Deposit area, ha</td>
<td>&lt;&lt;0.1</td>
<td>0.1 to 10^-1</td>
<td>10^-1 to 10^-1</td>
<td>10^-1 to &gt;10^-1</td>
</tr>
<tr>
<td>Deposit depth, m</td>
<td>0.1 to 3 m</td>
<td>1 to 5</td>
<td>5 to 15</td>
<td>&gt;10 (often 40 to 60)</td>
</tr>
<tr>
<td>Flux rates tph</td>
<td>0 (batch); 1 to 10 (lab and field)</td>
<td>30 to 300</td>
<td>4000 to 8000</td>
<td>5000 to 20,000</td>
</tr>
<tr>
<td><strong>Extraction Scales</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flux rates m^3/hr</td>
<td>0 to 2 (0 to 10)</td>
<td>2 to 20 (10 to 100)</td>
<td>1000 to 7000 (5,000 to 30,000)</td>
<td>1000 to &gt;20,000 (5000 to &gt;100,000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4 to 15&quot; line)</td>
<td>20 to 24&quot; line</td>
<td>24 to 30&quot; line</td>
</tr>
<tr>
<td>Ore mass (tonnes)</td>
<td>0.001 to 30</td>
<td>20,000 to 200,000</td>
<td>5 m to 20 m</td>
<td>300 M to 3 B (200,000 to 500,000 tpd)</td>
</tr>
<tr>
<td>Mass flux rates tph</td>
<td>0 (batch); 1 to 5 (continuous)</td>
<td>100 to 1000</td>
<td>3000 to 8000</td>
<td>5000 to 20,000</td>
</tr>
<tr>
<td>Volumetric flow rates m^3/hr (usgpm)</td>
<td>0 to 2 (0 to 10)</td>
<td>2 to 20 (10 to 100)</td>
<td>1000 to 7000 (5,000 to 30,000)</td>
<td>1000 to &gt;20,000 (5000 to &gt;100,000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4 to 15&quot; line)</td>
<td>20 to 24&quot; line</td>
<td>24 to 30&quot; line</td>
</tr>
<tr>
<td>Water Treatment Scales</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processed volume, m^3</td>
<td>&lt; 0.5</td>
<td>10 to 50</td>
<td>0.5 to 5 Min^-1</td>
<td>1 to 20 Min^-1 (Much higher for reuse)</td>
</tr>
<tr>
<td>Volumetric flow rates m^3/hr (usgpm)</td>
<td>&lt; 0.2 (&lt; 1)</td>
<td>1 to 10 (5 to 50)</td>
<td>100 to 500 (500 to 2000)</td>
<td>100 to 3000 m^3/hr (500 to 15,000) (Much higher for reuse)</td>
</tr>
</tbody>
</table>
1.8 Technology Categories

Figure 1-9: Roadmap Technology Categories

Oil sands tailings are a waste by-product of the mining and bitumen extraction process. To capture technology opportunities at various stages of the process and acknowledge the “end-to-end goals” of the study, a classification system (Figures 1-9 and 1-11) was developed that follows the various steps for forming and storing tailings materials in the mining life cycle.

The main categories are described as follows:

- **Mining:** Activities from the original geological exploration, through mine planning and mining operations, until the ore reaches the crusher. In terms of this study, mining technologies for improved tailings management are mainly focused on fines management by selective mining.

- **Extraction and Bitumen Recovery:** Activities from the crusher, through ore transport and bitumen recovery, to the point where the tailings (and other non-bitumen) streams leave the primary separation vessel (PSV) or secondary treatment cells. The focus is on process management to improve the behaviour of the tailings.

- **Tailings Processing:** Treatment of tailings at any point from the extraction vessel to the end of pipe at the tailings deposit, and any process that is decoupled from the primary bitumen extraction operation (reprocessing).
• **Deposition and Capping**: Activities involving tailings from the end of the discharge pipe to creation of a reclaimable surface.

• **Water Treatment**: Passive and active water treatment for re-use or release.

• **Reclamation**: Post-tailings activities including re-grading, soil cover, re-vegetation, monitoring and maintenance to achieve specific landscape performance goals and mandated end land uses. See Figure 1-10.

![Figure 1-10: Example Of Marsh Reclamation on Oil Sands Soft Tailings](image)

1.9 **Study Methods**

The following methods were used to provide a foundation of information from which the CTMC could develop a tailings technology roadmap / action plan:

- **Identifying Technologies**: The Component 1 team cast a very broad net to identify tailings and related technologies worldwide, using a variety of methods.

- **Networking**: The Component 1 team canvassed AI-EES, government regulators, CTMC member companies, OSTC representatives, and other colleagues for names of technologies.

- **Literature Review**: Using public databases, literature was selected and reviewed. All the Tailings and Mine Waste conference proceedings were canvassed. Internet searches were performed.

- **Previous Studies**: Tailings screening studies from OSTC members were reviewed.

- **Advertising**: Ads were placed in the Calgary Herald, The Edmonton Journal and The Globe and Mail on May 28, 2011 by AI-EES.

Initially, each technology that was identified received a unique number and was captured in the Master Technology List. In the end, over five hundred technologies were identified. This initial large list was evaluated for duplicates and similar technologies, and was reduced to a shorter
list of 101 unique technologies. The initial large list included a number of chemical amendments to existing technologies, which have now been included as technology enhancements rather than unique technologies. Variations of unique technologies were grouped together as part of the initial exercise.

Seven existing studies / technical papers were of particular applicability to Component 1 work:

- A Geotechnical Perspective on Oil Sands Tailings (Sobkowicz / Morgenstern, 2009).
- History and Developments in the Treatment of Oil Sands Fine Tailings (Sobkowicz, 2010).
- Oil Sands Tailing: Reclamation Goals & the State of Technology (Hyndman / Sobkowicz, 2010).
- Oil Sands Technology Review (BGC Engineering Inc., 2010).
- Oil Sands Technology Roadmap – Unlocking the Potential (Alberta Chamber of Resources and Secondary Contacts, 2004).
- Review of Reclamation Options for Oil Sands Tailings Substrates (BGC Engineering Inc., 2010).
- Screening Study of Oil Sand Tailing Technologies and Practices (Devenny, 2009).

A datasheet was designed to capture the information for each technology. The technology datasheets themselves do not appear in this report as they were never intended for public release, but Figure 1-12 is an example of a technology sheet that was used for this process. The sheet was filled out for each technology with the best available information. Additional information was stored electronically as "back up" or reference data.

Figure 1-11: Tailings Technology Selection by Category
## CTMC Component 1 Technology Description Data Sheet

*(Short form v1.2)*

<table>
<thead>
<tr>
<th><strong>Name:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Technology number</strong></th>
<th><strong>T-xxx</strong></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Category:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

### How it works:

### a.k.a.

- Stage of technological development in oil sands
- Potential for fluid fines reduction
- Practicality of Operation
- Site conditions
- Geotechnical
- Environmental Impact
- Regulatory compliance
- Cost

### Technology notes

<table>
<thead>
<tr>
<th><strong>References</strong></th>
<th><strong>Reports</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Publications</td>
</tr>
<tr>
<td></td>
<td>Pilots / prototypes</td>
</tr>
<tr>
<td></td>
<td>Commercial users</td>
</tr>
<tr>
<td></td>
<td>Patents</td>
</tr>
<tr>
<td></td>
<td>Proponents</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date of short-form completion and names of authors filing out form</th>
</tr>
</thead>
</table>

---

**Figure 1-12: Tailings Technology Sheet – Blank Form**
1.10 Third-party Vendors

The Component 1 team investigated oil sands technologies being developed by third parties to enrich the total list of technologies included in the roadmap. The investigation of third-party technologies was aimed at developing a broad list of oil sands technologies not currently being used at the commercial scale, which could be potentially viable for tailings management. We developed a list of third-party vendors and their associated technologies based on various suggestions from the OSTC, AI-EES, CTMC and oil sands vendor community, our literature search, and the newspaper ads listed above.

This third-party information gathering began on May 27, 2011 and actively soliciting new technology ended on September 31, 2011. The new technologies received after this time are included on a separate list for future evaluation.

Each vendor was required to submit a signed disclosure agreement (making any information submitted potentially part of the public record), to complete a tailings technology description data sheet for their technology, and to submit electronic copies of any supporting documents that they wished to share. Any information from any vendor who refused to sign the disclosure agreement was not accepted. All vendors who were interested in the program and provided the necessary documentation required by the CTMC are considered as having technologies to be investigated for the roadmap.
2. **LISTS OF TAILINGS TECHNOLOGIES**

A major portion of the Component 1 work scope involved soliciting, classifying and collecting data for tailings technologies.

The information is organized into five lists of technologies, as shown in Appendix B and described below:

- **Master Technology List**: List of 101 unique technologies organized by category and stage of development. The list includes the unique third-party submissions. In addition to the technologies on the Master List, fifteen technologies were added by the C4 Team near the end of the study. These technologies are not included in the statistics for the rest of this C1 report, but they are important technologies in the C4 report.

- **List of Technology Variations**: Thirty-two third-party vendors provided technology information for options that did not appear to be unique based on the information available. These technology variations are listed by name and affiliation. They are also included in the Master List but not on a standalone basis.

- **List of Technology Enhancements**: Twelve technology submissions were chemical amendments. These chemicals were collated on a separate list.

- **List of Remaining Technologies**: Twenty-seven third-party submissions were out of scope for this Project and others did not provide enough information for classification. These remaining technologies were recorded and noted on a separate list for the record.

- **List of Technology for Later Follow-up**: Technologies that were received after the cut-off date were included in another table.

Some of the remaining technologies relate to management systems, operational control and monitoring. There is an opportunity for further development of monitoring techniques (slurry flow metres, slurry fines content meters, density meters, and field sampling techniques, remote sensing, etc.) that are not covered in this report. There is also an opportunity for continuous improvement and enhanced governance and management of operational control systems for oil sands tailings. AI-EES and the OSTC should consider seeking out opportunities and to develop more reliable and robust methods of slurry and depositional monitoring.

### 2.1 Master Technology List

Table 2-1 below shows a summary of the number of unique technologies from each technology category, organized by stage of development. The table and the graphical representation of the data (Figure 2-1) show some important trends as follows:

---

2 Throughout the document, **statements made in italics are conclusions of the Component 1 Team. Statements in bold are recommendation made by the Component 1 Team based on the work to date.** The recommendations are also gathered in Chapter 10.
There are only eight technologies in use elsewhere, that were previously not considered for use in the oil sands; six of these are water treatment technologies.

The largest numbers of technologies (approximately 60%) reside in the tailings processing and deposition categories.

There are 25 technologies currently in practice at a commercial scale in the oil sands industry.

Third-party vendors have provided information in support of 22 technologies (six have been piloted and 16 are in the research stage) on the master list. A number of others are included on the master list and are variations of unique technologies.

Table 2-1: Master Technology List Summary Table

<table>
<thead>
<tr>
<th>Category</th>
<th>Commercial</th>
<th>Prototype</th>
<th>Pilot</th>
<th>Research</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Industry</td>
<td>Third-party</td>
<td>Industry</td>
</tr>
<tr>
<td>1. Mining</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>2. Extraction</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3. Tailings Processing</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. Deposition</td>
<td>11 (1)*</td>
<td>2</td>
<td>9</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>5. Water Treatment</td>
<td>3 (6)*</td>
<td>8</td>
<td>2</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>6. Reclamation</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>TOTAL</td>
<td>32</td>
<td>7</td>
<td>28</td>
<td>6</td>
<td>13</td>
</tr>
</tbody>
</table>

*Numbers in parenthesis represent technologies not currently being investigated for oil sands but used in other mining areas.
A thorough high-level assessment of available tailings technologies has been carried out. There is an opportunity to use the classification framework further. It is recommended that AI-EES and the OSTC develop a scanning framework for watching for new technologies as they arrive, to augment the database and funding of further research into new technologies.

### 2.2 Results from Third-party Vendor Initiative

Phil LeSueur, a member of Component 1, contacted 85 vendors regarding 97 technologies. Vendors were invited to send publicly available information to the team, and details from 44 interested vendors on 55 technologies were received (see Table 2-2), of which 20 are unique (included as part of Table 2-1 above), 26 are variations, and nine are enhancements. From the remaining incomplete technology submissions, 11 had sufficient available information to compile a datasheet and are included as either unique technologies or variations.

<table>
<thead>
<tr>
<th>Table 2-2: Third-party Technology Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Category</strong></td>
</tr>
<tr>
<td>Vendor Supplied</td>
</tr>
</tbody>
</table>
### Technology Sheets Created by C1 Data Sheet

<table>
<thead>
<tr>
<th>Description</th>
<th>Technology Sheets</th>
<th>Created by C1</th>
<th>Data Sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>i. Unique</td>
<td>20</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>ii. Variation</td>
<td>26</td>
<td>6</td>
<td>32</td>
</tr>
<tr>
<td>iii. Enhancements</td>
<td>9</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>v. Vendor declined involvement &amp; little public information available</td>
<td></td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>vi. Outside study scope</td>
<td>2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>vii. Vendor information received past cut-off date</td>
<td></td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td></td>
<td><strong>97</strong></td>
</tr>
</tbody>
</table>

Some interesting findings:

- The exercise was very fruitful, but quite labour intensive. A very wide net was cast and many technologies were received, many known to oil sands companies, but some new ones as well.
- Most of the proposed (third-party) technologies are in the research stage, typically involving bench scale batch tests. A few are in the development stage.
- Many of the proposed technologies are actually suites (i.e. combinations of technologies) of up to a half dozen individual technologies, starting in extraction, through tailings, and even on to reclamation.
- Some vendors indicated that they chose not to participate as they already had other R&D initiatives underway, and either did not see the value or felt that the CTMC work might somehow upset their other R&D work. Industry players intervened in some cases to encourage the vendors to participate anyway, to which some vendors responded. One vendor has chosen to wait until after the CTMC work is complete.
- There was a wide range of completed information provided. Many of the claims made were not substantiated and additional work will be required if an operator wishes to pursue these technologies. In some cases a standardized set of laboratory tests would be helpful, particularly for evaluating chemical amendments.

The team was careful to track all correspondence with all vendors. Of the 14 companies who expressed concerns:

- The following ultimately completed the Disclosure Agreement: Boray Technologies Inc., Carbon Basis Ltd, OHT, IPERC, Verve, and Titanium Corp.
- No response was received from the following: Gradek Energy, Gocool Persaud, and Rainbow Water Systems.
- The following ultimately refused to sign the Disclosure Agreement: BASF, Canadian Wood Fibre Centre, Dupont, Penn State University, and R&D Innovative Solutions.
There are a large number of technologies in the research stage, most of which are being advanced by third-party vendors. The quality of the available data is highly variable and would benefit from some standardized laboratory tests and reporting. There is an opportunity for the industry to continue providing a mechanism for soliciting and evaluating third-party oil sands tailings technologies.

2.3 Notes from Technology Categories

The following are notes from the master technology list, organized by technology category:

- **Mining:** Only two technologies in mining were identified that could provide changes to tailings management. Selective mining to minimize fines has been previously evaluated but deserves new attention as a planning exercise. At-face mining has been advanced by some of the operators but currently remains dormant; it is unclear whether there are any significant tailings reduction opportunities from at-face mining based on available information.

- **Extraction:** Extraction (bitumen recovery) is a commercially competitive technology in the oil sands and was not the focus of the present study except where there is potential for change in tailings production or behaviour. Many of the third-party technologies focus on extraction as a first step. An overview of the current water based extraction methods is provided as part of the state of practice description in this report. It is noted that water based extraction methods are expected to dominate bitumen recovery technology until 2030 (Alberta Chamber of Resources, 2004).

- **Tailings Processing:** Conventional Tailings and Composite/Consolidated Tailings (CT from MFT) is the most prevalent commercial technology set. In-line thickening (typically combined with thin lift deposition) is an emerging technology in the early stages of commercial development. Chemical treatment of tailings with polymers or other additives is a common theme, especially among third-party vendors. Rapid advances in polymer technology make this area very interesting, especially when paired with other dewatering techniques.

- **Deposition and Capping:** Discharge, deposition and capping technologies have received less attention generally, perhaps because of the difficulty in controlling and monitoring these processes at commercial scale, especially where the tailings come to rest subaqueously or under MFT. Production of non-segregating tailings has produced mixed results at a commercial scale, with difficulty in keeping the tailings non-segregating during deposition. More robust technologies and/or better process and depositional controls are required. Thin lift deposition is currently a major focus in commercialization. Low evaporative conditions in the oil sands region and the complex rheology of the fine tailings makes this approach challenging at large operational scales, limiting annual thicknesses of tailings. There is room for considerable operational improvements as these schemes are being implemented. A firmer understanding of the physics of thin layer evaporation is emerging. Hydraulic sand capping of dense soft
tailings remains a strong contender for most situations, but requires water table control techniques for terrestrial reclamation.

- **Water Treatment:** Some water treatment technologies are mature in the oil sands, others are mature elsewhere. Modest laboratory testing and piloting, often by vendors with specially designed portable rigs/laboratories, are used to scale the technology.

- **Reclamation:** Reclamation can be simplified to three basic methods: terrestrial, wetland, and water capped. Considerable research in specific aspects of all these techniques is ongoing throughout the mining industry.
3. COMMERCIAL MINING AND EXTRACTION PROCESSES RELATED TO TAILINGS PRODUCTION

This chapter provides an overview of current commercial oil sands surface mining and extraction practices, in particular as they relate to the production of oil sands tailings (Figure 3-1). Oil sands mining, bitumen extraction and tailings management practices have evolved over the 45-year history of commercial production. The process for extraction of bitumen from the mined ore remains water-based, with hydraulic deposition of the sand tailings.

Oil sands deposits consist of dense, interlocked silty sands containing some (about 10%) interbedded hard clay layers. The predominant sandy units are very strong in the undisturbed \textit{in situ} state. Highwall stability is controlled by the weaker clay layers. Ore grade bitumen is mostly associated with the sandy material, which is hydrophilic. The bitumen also contains dissolved gas, predominantly methane.

The surface mining and water based extraction technologies that are used to break down and disperse the ore deposits in order to efficiently recover the bitumen, also lead to liberation of the clays that form the low solids content, fine tailings deposits in the tailings ponds. The development of improved tailings management starts with an understanding of current mining,
bitumen extraction and tailings management methods, which include the inter-relationship of the different processes themselves in a commercial setting.

### 3.1 Site Conditions and Planning Constraints

Site conditions (See Figure 3-2) significantly influence the mine and tailings plans for each oil sands project. In some cases these influences may simply affect capital or operating costs. However, in many cases the site conditions, and in particular the unique combination of site conditions for a particular project, may preclude adoption of specific technologies and / or development of strategies on the basis that feasible waste storage plans cannot be developed. Therefore, when assessing the suitability of tailings technologies or suites of technologies for a project, evaluations spanning the life of the mine are typically done to ensure the feasibility of the plans and to ensure the pros, cons, and risks related to technologies and plans are well understood.

![Figure 3-2: Mine and Tailings Planning Depends on Local Topography and Geology](image)

The following are some of the factors that influence the layout and sequence of mine pits, mining and tailings technology selection, and the layout of ex-pit and in-pit mine waste and tailings disposal areas:

- External-to-the-pit (ex-pit) and in-pit foundation geology.
- Suitability of mine waste for construction.
• Ore body geometry.
• Ore quality and distribution.
• Topography.
• Availability of ex-pit space for facilities.
• Presence of legacy fluid tailings inventories.
• Setting for establishment of operational and closure drainage patterns.
• Proximity to other mine operators.
• Geological definition and confidence.

There is no single tailings management strategy to suit all site conditions. Each site will have its own unique characteristics that will favour different technology suites. Approximate ranges of possible conditions for these factors and some conceptual implications for tailings management are discussed in more detail in Appendix C. Technology suites need to be evaluated hand in hand with each mine plan developed for each lease.

3.2 Open Pit Mining

When the original oil sands mines were opened in the 1960s and 1970s, the truck and shovel equipment then available was not of sufficient scale to practically operate at the production capacities needed for oil sands mining. The Great Canadian Oil sands (now Suncor Energy) mine employed large bucketwheel excavators adopted from the German brown coal operations. The excavated ore was delivered to long conveyors for delivery to the extraction plant. The Syncrude Mildred Lake Mine used large draglines to excavate the ore and place it in windrows. Bucketwheel reclaimers delivered the ore to conveyors for delivery to the extraction plant.

All operating and planned oil sands open pit mines now employ truck and shovel technology for both overburden removal and oil sands mining. These large mining operations typically use the largest available equipment (up to 400 T trucks and 100 T excavators) to efficiently remove the overburden and haul the ore to the extraction plant. Smaller, less efficient equipment is selectively employed for tasks other than bulk mining.

Overburden removal and oil sands mining progress with sequential “benches”, which are typically 15 to 17 m high as dictated by the capability of the mining shovels and waste-ore intervals. The overburden (as well as low grade oil sands centre reject or “interburden”) is hauled to disposal areas or, if the material is suitable, used to construct all or parts of out-of-pit or in-pit tailings dykes.

Shovel technology (Figure 3-3) is generally a mix of large electric cable shovels favoured for their reliability and low cost of operation, and diesel-electric hydraulic shovels, which are favoured for their ease of relocation and ability to selectively mine and reject mid-bench material. A large cable shovel will excavate over 100 tonnes of oil sands per pass. Hydraulic shovels have slightly lower capacity, but can operate with a similar to smaller bench height.
Shovel-based mining is somewhat selective in that “waste islands” can be bypassed and bench levels can be set above centre reject zones. However, there is restricted ability for large shovels to selectively mine within a bench. Thus, small bands of clay-rich (low bitumen content) oil sands are mined and included with ore feed, along with the richer and coarser zones.

*The large scale mining equipment used in the oil sands mining industry does not readily permit selective mining except where there are large contiguous blocks of low grade ore (waste islands). Opportunities to reduce the fines sent to the crusher should be considered during the planning stage.*

### 3.3 Bitumen Extraction

#### 3.3.1 Evolution of the Water Extraction Process

For over a century, there has been interest in methods to extract oil from the surface-accessible part of the Athabasca oil sands. Investigative work in the late 1800s and early 1900s was conducted by the Geological Survey of Canada and the federal Department of Mines. Through the vision of Alexander Rutherford (formerly Alberta's first Premier) and Henry Marshall Tory (founding president of the University of Alberta), Alberta took charge of experimental work to make this resource accessible by commercial technology. Dr. Karl A. Clark (Figure 3-4) was recruited from the Geological Survey of Canada to develop the means to exploit the resource. In 1920, Clark began research on the Athabasca tar (oil) sands for the newly established Research Council of Alberta, earning its first patent for the hot water process the next year. While much has been done to improve the reliability and energy efficiency of the process and to
bring a scale of material handling unimaginable to the early pioneers, the oil sands mining industry has been built on the foundation of that early work by Clark.

There has been considerable work in the years since Clark’s original study to understand the separation and flotation mechanisms that are the basis of the water-based extraction process. The interactions of water chemistry and clay can be complex and there can be differences in interpretation.

Natural surfactants are produced when oil sands are processed with the Clark method using sodium hydroxide (NaOH). The surfactants are the agents that act to optimize primary recovery from the process. They do this by lowering interfacial tensions and increasing interfacial charges for all the phases involved in the process (oil, water, and solids). The increased charges on both the bitumen droplets and the solid particles favour bitumen detachment from the solids, while lowered interfacial tension of the bitumen droplets and the air bubbles favours attachment of bitumen to air. In fact, the prediction was made that bitumen will engulf the air bubbles because the much decreased surface area of the resulting bitumen-coated air bubble is

Figure 3-4: Karl Clark (Photo from University of Alberta)
thermodynamically favoured. There is a critical concentration of natural surfactants, the same for all oil sands, which must be achieved to optimize primary recovery.

Increasing slurry pH by adding caustic is a convenient method to enhance bitumen liberation from sand grains, and minimize bitumen and clay coagulation to improve bitumen recovery and froth quality.

### 3.3.2 Current Water Based Extraction Process

The current practice for the bitumen production process consists of the following steps:

- Ore Preparation.
- Slurry Preparation and Hydro-Transport.
- Primary Extraction.
- Froth Treatment (Secondary Extraction).
- Slurry Transport of Tailings.

Figure 3-5 presents a schematic of bitumen production processes.

![Figure 3-5: Conventional Oil Sands Tailings Schematic](image-url)
Description of each step follows:

- **Ore Preparation**: The ore-haul trucks deliver oil sands from the mining face to a dump station hopper that feeds a primary crusher. Here the oil sands ore is sized to less than 400 to 600 mm in diameter and discharged to a stacking conveyor, which supplies a feed surge bin or stockpile typically holding 30 to 60 minutes of surge storage. This arrangement provides continuous feed to the slurry preparation and extraction process.

- **Slurry Preparation & Hydro-Transport**: From the dry surge bin or pile, the ore is conveyed into a slurry preparation system and mixed with hot water. The slurry is at approximately 50°C and 57% solids by mass. Sodium hydroxide is typically added to the process water to aid in the slurry dispersion, to control the pH of the process to be slightly alkaline and to generate natural surfactants to assist in liberating the bitumen from the solids. Several different slurry preparation and lump size management systems are in use.

The hydro-transport slurry pipeline performs the combined functions of “conditioning” the oil sands for bitumen separation from the solids matrix, while at the same time delivering the ore to the bitumen recovery section of the extraction process. The conditioning step not only liberates the bitumen from the solids to facilitate recovery, but in the process, also disperses the fines; the cause of fluid fine tailings. Locating the slurry system closer to the mining operation increases the conditioning time as the slurry travels to the extraction plant and reduces truck haul cycle times. This is the start of the tailings formation process as the bitumen, solids and water are mixed and delivered to the extraction plant.

Figure 3-6: Water-based Extraction
- **Primary Extraction**: Canadian oil sands deposits are “water wet” and contain a small amount (approximately 3 to 6% by weight) of connate water surrounding the mineral solids. This hydrophilic property of the mineral solids allows for efficient, high-capacity, low cost material handling; hydrophobic ore could not be efficiently processed with water-based methods. Athabasca bitumen is an extra-heavy crude oil, typically with a specific gravity of about 1.01, slightly greater than water. Efficient flotation recovery requires air bubble attachment to the bitumen fragments. Bitumen recovery employs a primary (natural flotation) recovery step, augmented by a secondary (induced flotation) step.

  - **Primary Recovery**: The hydro-transport slurry is diluted with water to control fines concentration and fluid viscosity in the bitumen recovery circuit. The slurry is fed to a large diameter separator vessel (see Figure 3-6) where the majority of the bitumen floats due to air bubble attachment introduced in the slurry preparation system. The resulting froth skimmed from the surface of the primary separator contains about 60% bitumen, 30% water and 10% mineral solids attached to the bitumen. A dense sand slurry tailings stream is withdrawn from the bottom of the primary separator and a sand-reduced “middlings” stream is withdrawn from the side of the separator. The middlings stream (sometimes referred to as flotation tailings) is subjected to secondary bitumen recovery. The sand tailings from the bottom of the primary separator may or may not receive secondary treatment depending upon the plant design.

  - **Secondary Recovery**: The secondary recovery system is based upon introducing air and shear to generate small air bubbles so that they come into contact with the remaining bitumen fragments. Various shear mechanisms and vessel configurations are used to accomplish this step.

    In early designs, a separate, highly aerated secondary froth was recovered from this circuit, which contained more water and solid contaminants than the primary froth. More recent practice has been to recycle this stream to the primary separator and produce a more consistent froth composition.

    *Water based extraction methods are mature technologies and are key to current oil sands economics. They are unlikely to be replaced without significant development of new methods, with proven economics and commensurate (step change) benefits to tailings.* (Further information about research and development activities of non-water based extraction follows).

- **Froth Treatment (Secondary Extraction)**: Bitumen froth recovered in the water extraction process contains about 60% bitumen, 30% water and 10% mineral solids. Froth treatment is the process for removal of solids and water before the bitumen can be processed with heavy oil refining technology (upgrading). The bitumen may be sent to a
dedicated site-based bitumen upgrader or it may be diluted with a lighter hydrocarbon such as naphtha or natural gas condensate and sent to downstream refining via the common-carrier pipeline network.

There are two forms of the froth treatment process. Both add a light hydrocarbon (called diluent or solvent) to lower both the bitumen density and viscosity. The water droplets and solids are then removed with centrifuges, cyclones or gravity settling vessels.

The naphtha-based froth treatment process uses a light hydrocarbon fraction derived from the bitumen upgrading process. In its original form, the diluted bitumen (diluted with 0.5 to 0.7 mass ratio of naphtha) is processed through two stages of centrifuging. The first stage, using solid bowl decanter scroll centrifuges, removes any coarse solids that could create excessive wear or plug nozzles in the second stage. An intermediate step using reverse-flush filters removes any oversize light or floating material that could clog the disc stack in the following step. The second centrifuging step employs solid nozzle-bowl, disc-stack centrifuges that remove most of the water and finer solids. Distillation is then used to remove residual water and recover the naphtha for re-use in the process. The bitumen is then ready for processing in a dedicated upgrader. The naphtha-based process leaves over 4% water and about 1% solids (mass percentage on bitumen basis) in the centrifuged product. This has two significant consequences:

- Chloride salts in the water remain in the bitumen after the diluent is distilled out. Chloride salts in crude oil can lead to extensive and severe corrosion in refinery (or upgrader) processes. For this reason, virtually all petroleum refineries desalt their crude oils as a first step in processing to avoid chloride corrosion as well as other fouling issues that may arise from salts in the crude. Corrosion can also be mitigated through use of higher cost, chloride-resistant metallurgy.

- Although the level of solids contamination (0.5 to 1% mass) seems similar to other crude oils, the ultra-fine clay solids (< 1 µm) remaining in bitumen produced from the naphthenic process have a large, active surface area. This means that crude oil de-salters used in conventional refineries cannot operate on this bitumen feedstock, even in the low proportions of the total crude slate. The solids must be mostly removed for the bitumen to be marketable to downstream refineries and capable of being transported through the common-carrier pipeline system.

These considerations led to development of the paraffinic froth treatment process.

The paraffinic froth treatment process (PFT) is used to reduce the level of salts and solids contamination in the bitumen product compared to that attainable with the naphtha-based process. The paraffinic process uses a light aliphatic hydrocarbon such as pentane or pentane/hexane in place of naphtha as the process solvent (or diluent). Greater ratios of dilution are used in this process (typically 2:1) compared to the naphtha-based process. Originally developed by Syncrude to achieve more complete froth water removal and thus avoid excessive chloride contamination in the bitumen, the
process has the additional benefits of removal of the ultra-fine mineral solids so that the bitumen can be processed through a de-salter in a conventional refinery. The asphaltene (high molecular weight oil) content of bitumen produced in the PFT process is reduced typically by about one-half, an important matter for downstream upgrading. The PFT process relies upon precipitation of a portion of the asphaltenes in the bitumen to agglomerate the fine solids and free water. Operators who wish to produce fungible, market-grade bitumen, or who prefer to avoid the chloride and fine solids contaminants in the upgrader, employ the paraffinic process:

- Shell first commercialized the process for the Muskeg River Mine using a pentane-hexane solvent available from the Scotford Refinery.
- Shell Jackpine recently commenced operations with a high temperature design process based on the pentane-hexane solvent used for the original atmospheric design.
- Imperial conducted pilot work for the Kearl Project, now under construction, which incorporates high temperature paraffinic froth treatment based upon pentane solvent.
- Technologies to process froth treatment tailings are under development.

**Integration with Tailings Disposal:** Tailings are formed as a result of these different steps in the process of recovering bitumen from the ore body. There are two types of tailings streams: extraction tailings and froth treatment tailings. Extraction tailings, which contain most of the residual bitumen and mineral solids (about 90% of the solids) are derived from the primary and secondary recovery circuits. Both extraction and froth treatment tailings are separately transported by slurry pipeline directly to the tailings ponds and/or to tailings processing facilities.

Extraction tailings from the primary and secondary recovery circuits typically contain less than 1% dry weight of bitumen and fines contents ranging from 15 to 25% (by mass), depending on the ore body characteristics. The clay mineral component of the fines causes the generation of fluid fine tailings. Typical properties of oil sands extraction tailings are summarized in the next section.

Tailings from the froth treatment processes are sent to a recovery unit, where heat and steam stripping are used to recover additional diluent (solvent) for both economic and environmental reasons as described below. Froth treatment tailings are comprised of unrecovered bitumen, residual diluents, fines and water. Froth treatment tailings are typically placed into tailings ponds along with extraction tailings. There appears to be a lack of well documented information on froth treatment tailings. Bacterial action in froth tailings, resulting in methane gas generation, is thought to be promoted by the presence of light hydrocarbon (residual process diluents/solvent). Acid generation may in some cases result from the presence of sulphur compounds, including iron pyrite. In addition, concentrations of naturally occurring radioactive material have been reported in froth
tailings, albeit at low levels. For these reasons, some operators are pursuing alternative treatment and disposal options including thickening and disposal in pit.

There are outstanding concerns regarding the carryover solvents, pyrite and metals, and naturally occurring radioactive minerals (NORMS) in the froth treatment tailings. It is unclear whether these materials form discrete deposits or are diluted along with the extraction tailings after deposition. The existing froth tailings deposits be characterized and that process methods to reduce or manage these loadings be given a high research and development priority.

### 3.3.3 Process Water

A total of about three cubic metres of fresh water are required to produce one cubic metre of bitumen. Of the water requirements, about 20% is imported from the river to make up for the amount retained in tailings plus evaporative losses. The imported river water is clarified and used preferentially for producing boiler feed water and makeup for evaporative cooling, where low ionic content is advantageous. The remaining 80% is recycled water used to process oil sands. Variation in river import between operations primarily results from the amount of surface water runoff incorporated into the recycle water system, and the state of dyke building and consequent degree of saturation of the sand dykes, with smaller variation resulting from differences in MFT generation and the amount of evaporative cooling. Therefore opportunities for significant water conservation with the extraction process are limited once the recycle water inventory (clear water zone) has been optimized.

Typically, the oil sands recycle process water contains suspended solids, dissolved organics (i.e. naphthenic acids and surfactants), and various types and amounts of inorganic ions, among which the dominant ions are sodium, chloride, bicarbonate and sulphate, with a small portion of the divalent cations of calcium, magnesium and potassium. These ions make their way into the process water by being released from the associated connate (formation) water of the oil sands ore, ion exchange on the clay minerals, addition of process aids to extraction and tailings treatment, and to a lesser degree, the net import of local surface water to the recycle water system.

Initially, the dissolved salt concentration of the process water progressively increases as a result of the connate water salinity in a closed system. Pseudo equilibrium water chemistry conditions are reached between ions entering recycled water, water losses and dilution due to river water import. Dilution by new water is major contributor to the pseudo equilibrium conditions because large volumes of process water are removed from the water balance by sequestration in sand and fine fluid tailings deposits.

As ionic concentrations in process water are known to play a major role in bitumen extraction recovery from oil sands, ionic concentration is monitored, predicted through modeling and, where appropriate, management actions are undertaken to sustain acceptable bitumen recovery and bitumen froth quality.
4. COMMERCIAL TAILINGS PROCESSING, DEPOSITION AND CAPPING

All current and planned oil sands mining operations have adopted water based extraction for bitumen production. Older facilities (Suncor and Syncrude Base Mine) use a form of the original Clark Hot Water Extraction (CHWE) process and newer facilities have adopted the Low Energy Extraction (LEE) process initially developed by Syncrude for use at the Aurora North project. This chapter reviews the various tailings strategies that are currently in use to process water based extraction tailings, the slurry transport methods used to deposit these material, and the practices for constructing a trafficable surface amenable for placing reclamation material. As a precursor to this discussion there is a review of the basic tailings properties.

4.1 Tailings Properties Overview

This discussion is based on current commercial water extraction tailings and has mostly been derived from overviews presented in OSRIN (2010) and Sobkowicz (2009).

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 layers illite/smectite (Chalaturnyk et al. 2002). It is believed that illite and mixed layer clays are largely responsible for the processing and dewatering challenges 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 (see Figure 4-1) and for the ion exchange mechanism in the tailings ponds (Chalaturnyk et al. 2002).
Oil sands tailings are comprised of sand, fines, process water and residual bitumen. Approximate properties of the slurried materials and the resulting deposits are usefully illustrated on the slurry properties diagram which is a ternary plot showing the different proportions of solids (sand and fines) and water. Scott (2005) used the ternary plot to illustrate areas with different geotechnical behaviour of the tailings, as shown in Figure 4-2 below.
For mixtures with a fines-dominant matrix, it is the relative amount of fines and water (irrespective of the sand content) that determines sedimentation vs. consolidation behaviour, liquid vs. solid behaviour and to some extent, segregating vs. non-segregating behaviour in the tailings.

The fundamentals of the formation of high water content 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 that promotes dispersion of the particles, inhibiting their sedimentation and consolidation. Dispersion of the clays, which is necessary for efficient bitumen extraction by floatation, prevents rapid dewatering (sedimentation and consolidation) of the tailings clays. Adding sodium ions (as caustic) to the oil sands extraction process exacerbates this condition as far as tailings disposal is concerned. However the consolidation behaviour impact of fluid fine tailings does not appear to be drastically impacted by the process water chemistry after initial sedimentation.

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 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: electrostatic, steric, Van der Waals, and hydration (FTFC 1995). 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 modelling of the fine tailings dispersion.
- MFT morphology and characteristics.
- Sand, clay, organics, oil 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 \( \mu \text{m} \) and 10 \( \mu \text{m} \).
- The average solids content of MFT is about 33\%, equivalent to an average void ratio of 5.
- The hydraulic conductivity of the MFT is in the range of \( 10^6 \) to \( 10^9 \) 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\%.
- This viscosity varies from 0 to 5000 cP and it increases as times passes (after it is disturbed or deposited). This time dependent reversible behaviour is termed thixotropy.
- MFT shear strengths are typically much less than 1 kPa (i.e. it acts as a fluid).

### 4.2 Review of Commercial Tailings Technologies

Tailings management in the oil sands has evolved since mining was initiated in the region and three overlapping periods of tailings technology development can be considered. Tailings technologies from all three periods of development are still in use today, mostly in combination with one another:

- **1960s through 1980s**: The focus was on waste management (materials handling and geotechnical stability). Numerous large dams were constructed from tailings and to hold fluid fine tailings, space was left in mined out pits for long-term storage of fluid tailings, and the focus was on constructability, safety, and cost. Tailings technologies that have evolved from the early years of oil sands mining are referred to here as “conventional tailings.”

- **1990s through 2000s**: The focus was on creating solid tailings landscapes capable of supporting terrestrial reclamation and land uses. This included research, development, and implementation of sand capped composite tailings, and ongoing research and development of water capped MFT end pit lakes. Tailings technologies that were developed during this period are termed “process tailings” for the purpose of this report.

- **2010s**: The focus was on meeting new regulatory goals to reduce production and legacy volumes of fluid tailings, and to speed reclamation. This has resulted in rapid research,
development, and implementation of high fines, soft tailings technologies. All these technologies currently involve managing MFT inventories and are referred to here as "emerging technologies."

The individual technologies developed during these periods form combined "suites" of technologies that meet various performance objectives within the overall tailings plan for a project. We have identified eight suites that draw upon 21 different technologies. Some of the technologies have not been classified as commercial in the Master Technology List. However they are included here in the eight suites as they are in the early stages of commercial implementation. Table 4-1 shows a summary of the different suites and the technologies employed within each of them. Sketches of various tailings disposal techniques are presented in Figures 4-7 to 4-14.

Perhaps not surprisingly, almost all of the suites rely upon slurry discharge methods, tailings consolidation, water recycle, and mechanical capping for reclamation. The first three methods are reasonably mature, but mechanical capping at this scale is largely unprecedented and likely to be very expensive. Current regulations (especially ERCB Directive 074) are focused on the shear strength of the soft tailings only, whereas trafficable surfaces require compatibility (both the placement methods, strength, and density), between the cap and the underlying soft tailings. There is a need to review current plans and regulations for stabilization, capping, and reclamation of soft tailings deposits. Placement methods need to be re-examined for compatibility of material properties (both capping materials and underlying tailings), the scale of the operation, costs, and the desired landscape performance. The various methods for hydraulic capping should be included in this evaluation.

Figures 4-7 through 4-13 provide schematics of the commercial suites. Appendix D provides more detailed summaries of the commercial processes.
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<th>Commercial Suite</th>
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<th>Deposition</th>
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<td>Conventional Hydraulic Fill Construction</td>
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<td>Water CAPPED MFT</td>
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Note: Technologies in red are pre-commercial, those in green are in commercial use in the oil sands.
4.2.1 Conventional Tailings Technologies

All current and planned operations have or plan to use conventional tailings as part of their overall tailings management system, especially during early years when there is no space for depositing tailings in the mined out pit areas. This is the primary tailings method for managing out-of-pit tailings (whole tailings discharge) and most projects have some component of water capped MFT; these are the two suites referred to here as conventional tailings.

Conventional Hydraulic Fill Construction

The tailings resulting from the Clark Hot Water Extraction process and its modern derivatives produce a segregating\(^3\) tailings slurry (see Figure 4-2). The slurry is conveyed by pipeline and discharged into a disposal area, on the inside of a sand or overburden dyke, forming “beaches.” Upon discharge, the coarse sand settles rapidly from the slurry, leaving a water runoff that carries with it a portion of the fines (clay and silt), which forms a “pond.” In general practice, sand cell construction is used to construct the dykes; sand and fines are captured in the cells and beaches; and the pond contains process water with fines that run off as the beaches are formed. The fines settle, forming a “clear water zone” near the surface of the pond, which is recycled for use in the extraction process. An alternative to tailings sand-cell construction is to raise all or part of the pond containment dykes using earthen construction sourced from overburden or oil sands reject interburden (the lean oil sands seams within the orebody).

The basic tailings disposal method is to discharge whole tailings and/or cyclone underflow tailings as a single stream and either beach the sand to the interior of the tailings pond or use it for cell construction of the pond containment dykes. Typically, dyke cell construction uses a method called “modified centre line” or “upstream construction” where the cells are constructed over the previous beach area. As an integral component of the dam, that portion of the beach must have geotechnical integrity. Wide track dozers are used to compact the sand cells and sometimes the beach areas that make up the containment structure. In the latter, sufficient density is often achieved by sufficient downward drainage under the beached sand, which occurs if the pond level is well below the discharge point and the portion of the beach above the water line has a low fines content.

Conventional hydraulic fill construction is a proven and secure method to manage oil sands tailings. The major issues relate to the fluid fine tailings that segregate during deposition to form first TFT, and then with time, MFT. Also, bitumen and solvent losses from froth treatment are significant contributors to floating oil on the recycle ponds and to operational difficulties with bitumen “mats” in the fluid fine tailings. Solvent on the pond surface contributes to atmospheric VOCs with HSE implications and acid generation has been reported due to pyritic sulphur. The potential for acid-generation from dewatered, near-surface FTT deposits under reclamation needs further investigation. Increased concentration of low level NORMs (naturally occurring radioactive material) has also been reported in FTT deposits.

There are often other minor waste streams directed out to the tailings ponds.

\(^3\)That is, the solid particles separate according to grain size.
Conventional tailings continue to offer benefits necessary for efficient oil sands operations:

- Low cost slurry transport.
- Mature technology with well-developed engineered containment design and construction methods.
- Segregation allows efficient cell construction.
- Handles a wide variety of conditions (low or high fines, low or high bitumen, low or high solids, can include other low volume waste streams).
- The pond is an efficient “vessel” for clarification of process water and initial sedimentation.
- New findings, from Syncrude’s Aurora Settling Basin and Suncor’s Pond 1, show that 70 to 75% of the fines reporting to the basin are trapped within the tailings sand, mostly as Beach Below Water (BBW) or perhaps more specifically as Beach Below MFT. This is a larger fines capture than is typically assumed during initial design stages.

There are numerous opportunities for improvement:

- Reduce transport distances.
- Reduce fluid content.
- Reduce ionic loading.
- Control of dusting and sand deposition.
- Reduce large quantities of fluid fine tailings.
- Improve consolidation rates and strength gain rates for fine tailings.
- Improve sand permeability for water table control.
- Reduce propensity for erosion on downstream dyke slopes.
- Reduce head losses and wear on pipes and pumps.
- Improve fines capture in settling basins. These sandy, fines rich deposits end up sequestering most of the fines from the orebody.

There is opportunity through more engineering and operational efforts to further increase the fines capture rate, thus reducing the MFT production rate. **This opportunity for “managed beaching” should be investigated through fundamental work and large trials.**

**Water Capped MFT**

Water capping of MFT within a lake created by a completed mine pit has been under development by Syncrude since the early 1980’s (see Figure 4-3). After 30 years of small-scale demonstration, culminating with a 4 hectare pond under observation since 1984, this most studied of methods is now being tested in a commercial scale demonstration at Syncrude’s Base Mine Lake Project. Transfer of some 200 million cubic meters of MFT into the 800 ha pit, west of Highway 63 South at the Mildred Lake site is underway, with water capping to be completed in 2012.
While this project is being conducted within an operating mine, Syncrude and other operators await the assessment of this commercial scale demonstration, as in-pit, water capped sequestration of MFT is a proposed component of closure plans for all mines now in operation. Predominant technical matters to be verified include:

- Lake performance
- The rate of bio-degradation of naphthenic acids in the process water cap
- The potential for re-disturbance of the settled tailings
- The potential for permanent or semi-permanent stratification
- The rate of release water from the underlying MFT at large scale
- The potential for mixing of lake bottom sediments with surface water due to wind effects

This technology is a sequestering technology and accepts that the MFT will consolidate over a very long time period in the range of hundreds of years.

An opportunity that should be evaluated with water capping is to increase the density of the MFT placed at the lake bottom either by flocculation and placement or flocculation, centrifugation and placement. This would allow for a significant reduction in MFT sequestered...
providing for low-cost deposition. In addition, the greater density difference between the water layer and mud layer reduces the risk of mud turnover. Further, the higher density means there is less water, containing naphthenic acids, remaining in the deposit to migrate into the lake water layer.

4.2.2 Process Tailings Technologies

During the 1990's tailings management practices focused on conversion of fluid fine tailings into semi-solid deposits that were amenable to capping for terrestrial reclamation. Co-disposal of coarse and fine tailings (CT) was researched, developed, and implemented at Syncrude and Suncor, and is now a major commercial technology. Thickened tailings (TT) was piloted by CONRAD at the Syncrude Aurora site, and is in use at Shell’s Muskeg River and Jackpine Mines.

Both CT and TT have the potential to reach their goals of reducing fluid fine tailings inventories, creating more solid landscapes, and providing more terrestrial reclamation. A dominant challenge has been in the day-to-day, all season operation of the processing equipment to produce robust, non-segregating, fast consolidating slurries. Also there is a need for better management of off-spec materials, and improved methods to monitor field deposition processes at large scale and in difficult operating conditions.

Composite Tailings (CT) and Non-segregating Tailings (NST)

Composite / consolidated tailings using MFT as a feedstock was piloted at both Syncrude and Suncor with excellent results. Much of the sand capped area at Syncrude’s CT Prototype was reclaimed ten years ago and is performing well. Syncrude’s 10 Mm³ CT Prototype deposit has been held up as the ideal for CT that is a dedicated disposal area, single discharge point, high spec CT, with a successful sand cap and reclamation. Some elements leading to its success are difficult to duplicate commercially. These include partial separation from production, ability to discharge off-spec materials to other deposit, single discharge point, dedicated operational staff, full time technical oversight, almost entirely subaerial deposition, pre-installed instrumentation, close mass balance, shallow deposition and summer-only operation.

A limitation of CT is that the sand used in this process is unavailable for dyke construction, beaching or capping activities, and thus priorities must be set for sand use. Also, the CT must be fully contained while the deposition is underway. For these reasons the method is not seen as suitable for sites where out-of-pit or in-pit containment is unavailable or subject to high costs.

Full scale composite / consolidated tailings operation at Suncor proved disappointing, resulting in large volumes of high fines, low solids tailings that will be difficult to reclaim. The major issue was CT segregation when discharged below water and below MFT, despite the trialing of numerous discharge techniques. At Pond 5, a mechanically placed coke cap is being installed, along with tightly spaced wick drains, to speed consolidation of this segregated, soft “CT” deposit. Capping plans are in place for Ponds 6 and 7 at Suncor.

At Syncrude’s East In-Pit pond (EIP), the composite tailings was more robust and the deposit is nearing full height and being sand capped. Off-spec material was removed by an MFT / RCW
reclaim barge and transported to the West In-Pit pond (WIP). Unfortunately, for a variety of reasons, much of the deposit volume is composed of tailings sand due to off-spec CT and segregation during deposition. The remaining volume of high fines CT in the distal end of the deposit is being evaluated. Additional work is needed to understand full scale operations as partial success of the CT prototype was related to off-spec tailings deposition in the WIP.

Syncrude has recently started to place CT in the Southwest In-Pit area (SWIP) and is experimenting with commercial scale sub-aqueous tremmie discharge. A large CT plant is being designed and constructed for Syncrude Aurora North East Pit. CNRL is constructing facilities for NST (combined TT and tailings sand using a thickener that results in a material similar to CT) at their Horizon Project. Is it thought to have similar benefits and challenges as CT from MFT.

Some of the benefits of CT and NST technology at commercial scale include:

- Deposits strong enough and dense enough (if on-spec) to allow hydraulic sand capping.
- Rapid release of process affected water during deposition, available for recycle.
- Consolidation settlements complete in 0 to 20 years, typically with 0 to 4 m of post reclamation settlement, manageable with a well designed sand cap.
- Some reduced toxicity of release water. Release water is clear.
- Ability to control coarse and fine inputs and coagulant dosages in real time.
- Ability to create deposits that provide about 30 to 50% upland and 50 to 70% wetland land uses.

And there are areas for potential improvements:

- There can be difficulty in creating non-segregating deposits, largely due to un-optimized discharge methods. Off-spec CT is difficult to remobilize (without dilution), or to cap, essentially behaving as sandy MFT.
- Surfaces are untrafficable to mining equipment even when consolidated, and must be capped with sand hydraulically or mechanically (or capped with water).
- Large bulking factors requiring a large containment volume per tonne of fines.
- Deposits are loose and hence essentially permanently liquefiable, requiring robust or geologic containment. The potential for liquefaction of the upper part of the deposit must be considered when designing and constructing closure landscapes.
- Calcium and sulphate in the recycle water has detrimental impacts for re-use in the plant, and impacts on aquatic organisms.
- Large quantities of tailings sand are consumed, leaving little for dyke construction and sand capping.
- Overall “bulk” lines capture rates need to be improved; the loss of fines when the CT is off-spec and when one includes the losses associated with sand capping and dyke construction is higher than originally envisioned during CT development.
• There are residual concerns regarding potential production of hydrogen sulfide (H₂S) by anaerobic bacteria feeding on the elevated levels of sulphate in the future.

There is opportunity to examine the engineering properties of lower SFR CT (nominally 3:1) that would reduce the reliance on sand for CT production, increase the fines capture, and potentially provide better non-segregating behaviour. It can also be concluded that producing higher density CT discharge would increase the fines capture and make a more robust operating system. More consideration should be given to lower SFR CT operationally and that High Density CT be further investigated. The results of the Shell Pilot revisited (see Table 6-1). More robust discharge methods should also be investigated.

Thickened Tailings

In a typical oil sands thickened tailings circuit the thickener is derived from a cyclone overflow stream. The underflow contains most of the coarse sand and is about 50% solids. Most of the water, carrying most of the fines, reports to the overflow. The fines stream feed to the thickener enters at 10 to 20% weight solids, at a sand to fine ratio of approximately 0.3:1 to 0.8:1 SFR. The thickener uses flocculants to enhance gravity settling of solids in water, with increasing density towards the bottom of the thickener. Clarified water from the overflow of the thickener is recycled back to the extraction plant for re-use in ore processing. The thickener underflow is densified to a solids target 45 to 55% and pumped for storage behind engineered containment. Density is limited by rake torque and pumping requirements.

The Albian Sands project operates commercial scale thickeners at both their mining projects as discussed below:

• The two high-rate thickeners installed with the original Muskeg River Mine were predominantly justified for the recovery of warm water for re-use in the extraction process. Thickener underflow has been discharged into the tailings settling pond in several different configurations. While significant segregation has occurred, some of these deposits are exhibiting consolidation behaviour.

• The Jackpine Mine, which commenced operation in late 2010, included a high-rate thickener with design improvements based on experience with the Muskeg River operation. Low fines content in the opening area of the Jackpine mine has resulted in TT production below the design range of the underflow system. Increased water must be withdrawn with the TT underflow to satisfy minimum flow rates. This has prevented any meaningful assessment of the ability to reliably produce on-specification TT. Design modifications are underway to provide for a greater range of fines in the oil sand feed.

Consistent operation of thickeners to produce a non-segregating TT product has not been accomplished at commercial scale. The primary driver for design of the entire thickening and deposition process is to achieve a deposit with acceptable fines capture, consolidation rates, density, and strength. The design includes the disposal area required to contain the tonnages, lift thickness and lift frequency and achieve the deposit performance that will support timely capping and consolidation consistent with reclamation plan commitments. Design of a robust thickener must accommodate the range and variations of feed expected from mining/extraction.
Consistent target solids and SFR to support a beachable TT could be a challenge with a high rate thickener.

An alternative of re-flocculation of the thickener underflow to achieve a permeable deposit that would release additional water has been considered but not fully explored or tested on a large scale. If a two-stage flocculation protocol could be successfully developed, this would make the method similar to the in-line thickening deposition methods discussed below as emerging technologies.

Some of the benefits of thickened tailings include:

- Rapid release of warm, process affected water suitable for immediate re-use in the extraction plant.
- Consistent underflow stream with reasonably good consolidation properties.
- Hydraulic transport to retention ponds.
- Formation of soft, but non-liquefiable deposits with properties of that of normally consolidated soils.
- No ionic loading of the recycle water stream.

Areas of improvement for TT include:

- Pre-conditioning of fines slurries for greater consistency before loading.
- Improved flocculents / flocculent additions for thickening and post deposition consolidation properties.
- Simpler, more robust thickener processes and process controls that can consistently produce a denser, non-segregating material.
- Documentation of commercial operating experience.
- Bitumen skimming from overflow.
- Better understanding of any potential polymer/monomer toxicity issues.
- Reduced costs.

There is opportunity for continuous improvement of many aspects of producing thickened tailings that will reduce costs and increase reliability. A systematic review of industry wide oil sands thickener operating and deposit performance should be considered, with a view towards a) improved reliability, and b) optimizing the SFR and density of the discharge, to maximize consolidation behaviour to form a cappable deposit. This will probably require a departure from high rate thickening towards thickener technologies that can readily produce and handle a denser underflow product, which may also have implications for pumping technologies.

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4Saturated TT deposits are, however, almost certainly strain softening.
4.2.3 Emerging Tailings Technologies

As the operational challenges and planning limitations of CT became more evident (e.g., containment volume requirements and competition for the use of sand), methods intended to solidify fines on their own, rather than blending fines with sand, received increasing attention.

Frustration at seeing legacy MFT volumes continue to grow, and the submissions of EPEA applications for new sites that would quadruple the amount of fluid tailings at the end of oil sands surface mining in forty years (despite adoption of processed tailings technologies) caused the ERCB to introduce new regulations to stabilize if not reverse the trend. ECRB Directive 074 (D074) was announced in February 2009 and has partially contributed to the drive towards a third wave of tailings technologies.

Since the release of D074, research and development activities have more than tripled, and several new technologies are at various stages of commercial development. Some of the individual technologies that form the “commercial suites” are still at development scale. This trend of rapid technology deployment with short implementation time frames, based largely on regulatory obligations, poses new challenges on the oil sands industry.

In-line Thickening with Thin Lift Dewatering

This method involves in-line treatment of MFT with an anionic polyacrylamide flocculent followed by thin layer deposition. This technique has benefited greatly from recent polymer advances, accompanied by new mixing / shearing / pipelining techniques. Dewatering is accomplished by a combination of sedimentation, shear during beaching, and under drainage, with additional environmental effects to increase solids content after deposition.

Following trials on the Suncor site initiated by polymer manufacturer SNF Floerger, Suncor further refined the method and adopted it as the primary component of its tailings reduction operations (TRO). The current practice is to deposit a thin layer (i.e. 10 to 30 cm). After initial dewatering to about 60% solids mass, the surface is reworked to break the crust and allow for atmospheric drying to increase the solids content towards design values. After one or two layers have reached sufficient solids content, the material is removed from the drying surface and relocated to waste dumps or kept in place.

Shell is deploying a similar method at its Muskeg River Mine, which also relies on re-handling the material. The current plan is to place the material in overburden dumps.

As originally contemplated, this method could be practiced by placing, and leaving in place, multiple layers of thin lift deposition over each summer season. Each layer would “dry” in-place to from a “solid” deposit. Subsequent lifts would be placed in succeeding years. At an annual deposition rate of 3 t/m² to 5 t/m², a placement area of 1 km² could support an operation of 3 to 5 million tonnes per year of MFT solids.

In practice, deposition rates require more area to sufficiently dewater the material. Only about 1 t/m² can consistently be treated in this manner. Even this rate produces material that may be too weak for building deep, multiple-layered, free-standing deposits to depths of 10 to 20 m. Challenges with this method include:
• Re-handling adds to the cost and requires sufficient volumes of construction-grade overburden for containment.
• The area required to operate the drying process plus the increased area required for secure overburden polders is very large.
• The availability of competent overburden material to manage both weak overburden units and the low-strength dewatered MFT.

![Figure 4-4: Suncor TRO Spigots](image)

There are significant opportunities to improve the In-line thickening / thin lift dewatering technologies including process, deposition, management, and cost. **As a first step to realizing these opportunities, the industry should conduct a thorough review of the performance of the field studies conducted at Suncor, MRM, and Syncrude.** The review should include a common basis – consistent definitions, a field database of performance, and a common understanding on the underlying physics of actual potential evaporation, as a building block towards improving this technology.

**In–line Thickening with Accelerated Dewatering**

This method, being developed by Syncrude, uses in-line flocculation of MFT followed by deposition into a containment area, either in deep in-pit deposits (> 20 to 30 m) or shallow polders (i.e. ≤ 5 m thick in sand cells). The method is an alternative for centrifugation and has similar containment efficiency (lowest volume per tonne of fines). It is expected to have the lowest cost and lowest energy intensity of any of the pond solids methods.
This method was piloted by Syncrude in 2009 in a 10 m deep, 60,000 m$^3$ deposit. Syncrude plans a larger trial for 2012 using improved polymer and polymer mixing technology developed since 2009 that could increase both initial deposit dewatering and subsequent consolidation. The method relies on having the ability to decant surface water expressed from the deposit along with precipitation. Self-weight consolidation is augmented with perimeter rim ditching and natural surface cracking to lower the water table. Starting at about one metre deep, the ditch is advanced many metres until the deposit is eventually unsaturated and over consolidated to partial or full depth. Perimeter ditching is widely used in Florida in the phosphate industry.

Ongoing monitoring of the Syncrude pilot should continue with a view to developing an understanding of the role of cracking and rim ditching on the densification behaviour.

**Centrifuge MFT**

In this method, the MFT, supplied from a pond dredging operation, is diluted to a controlled concentration (currently 20% solids), mixed with a polyacrylamide solution and centrifuged to a “cake” at 55 to 60% solids. The cake may be transported to a large engineered disposal facility by three different methods:

- Conveyor to stacker.
- Pumped with positive displacement pumps and transported by pipeline.
- Hauled by truck.
As currently envisaged at Syncrude, the planning basis is a 2 m per year deposit to take advantage of environmental beneficiation, mainly by freeze-thaw dewatering. Syncrude testing has demonstrated a capacity of up to 80 tph using a 1 m diameter, solid bowl, scroll decanter. A larger 1.4 m diameter prototype machine is undergoing testing.

The attractiveness of centrifugation is the reliability of cake water content under varying weather, terrain and feed conditions, coupled with the ability to operate for most of the year. Capital cost and large-scale depositional behaviour are the primary concerns.

This technology has a high potential for large-scale conveyor transport, both out of pit if there is room and in-pit. There is opportunity to reduce costs with development of larger diameter centrifuges and the use of a mobile or re-locatable centrifuge plant.

This technology has potential for broad application to MFT beneficiation, similar to that of thin lift drying. Testing to date at the Syncrude site indicates that a reliable cake solid is achievable at high production rate with the commercially available centrifuges. Studies are underway to evaluate conveyor stacker operations. Feasibility level evaluations would improve an understanding of the economics for different transport methods and provide an opportunity to optimize the material handling schemes based on results from the pilots to date.

**Coke Capping**

Petroleum coke is produced from the upgrading operations at Suncor, CNRL and Syncrude. Suncor and Syncrude burn a portion of their coke production for site steam and electrical energy. The coke at CNRL and Suncor comes from the Delayed Coking process. It is cut hydraulically from coke drums that are filled cyclically then taken off line for steam stripping residual volatiles and coke removal before being put back on line for coking. Delayed coke has the appearance of coal. The coke produced at Syncrude comes from the Fluid Coking process. It has been partially combusted in a fluidized bed, which is circulated to provide heat to the fluidized reactor bed. Consequently it is harder, denser, less porous and made of fine round grains. It has the appearance of black sand and is sometimes called "shot coke."

Oil sands coke has a high sulphur content, limiting its commercial use to supplying a portion of cement kiln fuel blended with low-sulphur coal, or similar use for thermal power. Transportation costs from Fort McMurray have limited its marketability and it generally has negative value to operators who are regulated to segregate its disposal for potential future use as an energy source. As a low-density aggregate, coke offers the opportunity of a lightweight capping fill on soft tailings.

At Suncor, delayed coke is being used to form a “floating cap” over the soft deposits in Pond 5 and Pond 6 resulting from segregated CT (See previous section on CT). The coke has been placed in a grid of roadways over a geo-membrane placed on the frozen surface in winter. Because the coke is less dense than the fluid tailings it floats on the surface providing access for equipment, monitoring and installation of wick drains. Eventually the surface will be covered and then sand-loaded to initially dewater and then fully consolidate the underlying deposit. Albeit costly, this is a means of in-place remediation of these soft deposits.
At Syncrude, the fluid coke has always been transported to its storage area in a water slurry. In a current test, the coke is being beached into MFT in the Mildred Lake Settling Basin. Here the coke settles through water into the MFT reaching its point of natural buoyancy.

Coke offers the opportunity of a lightweight fill on soft tailings, through beaching (Syncrude MLSB), mechanical capping (Suncor Pond 5) or by raining in (under consideration for Suncor Pond 6). Its value as a surcharge is limited by its low density, but with care, it can offer a trafficable surface for further loading, or installation of vertical drains for dewatering the underlying soft tailings. It should be noted that while coke capping is a commercial technology, it was not included by the Component 4 Team...

The opportunity to evaluate wick drain performance in soft tailings is one of the benefits of coke capping at Suncor Pond 5. The efficacy of wick drains in fluid fine tailings dewatering requires study and resolution.

### 4.3 Moving forward

There is an major opportunity to increase the performance and decrease the cost of existing commercial tailings technologies and suites employed at the oil sands operations. After the first draft of this report was released, the Component 4 Team addressed this opportunity by carrying out a gap analysis of the commercial suites to evaluate the potential for continuous improvement of existing technologies and addition of new complementary technologies.

There is also a major opportunity for improved management and governance of existing tailings technologies, applying the same management controls used to produce tight specs on bitumen...
and synthetic crude oil, to the planning and operation of tailings systems using a more conservative and managed approach to achieving desired tailings performance.
Figure 4-7: Conventional Hydraulic Fill Construction
Figure 4-8: Water Capped MFT
Figure 4-9: CT Composite / Consolidated Tailings
Figure 4-11: In-line Thickening With Thin Lift Evaporative Drying
Figure 4-12: In-line Thickening with Accelerated Dewatering
Figure 4-13: Centrifuge MFT with Conveyor / Stacking
Figure 4-14: Coke Capping of Soft Tailings Deposits
5. RECLAMATION AND WATER TREATMENT IN PRACTICE

This chapter provides an overview of reclamation practices and commercial water treatment systems in the oil sands industry. The methods outlined in this chapter are described at a high level because reclamation and water treatment in the oil sands are a developed industry and can relatively easily be fit to a wide range of tailings technologies. In other words, in most cases, existing technologies can be employed and it is fairly straightforward to develop and implement any additional techniques that may be required.

5.1 Reclamation

Reclamation involves resloping the land for surface water drainage, water table control, and topographic diversity; placement of reclamation materials; planting of initial vegetation; and modest monitoring and maintenance until one can be reasonably sure the resulting reclamation is on the right trajectory to becoming a useful component of, and fit into, the surrounding boreal forest (Figure 5-1). Where reclaimed wetlands, lakes and watercourses are involved, there is also a water management component to the reclamation in the early years.

Figure 5-1: Traditional Terrestrial Reclamation Steps
Reclamation involves re-creation of channels and streams to convey surface water safely from the reclaimed land back to the Athabasca River.

Ideally, reclamation is done with large mining equipment (200T+ trucks, D9 and D10 dozers). For softer areas, 100 T trucks and D6 to D8 dozers are often employed (but at higher cost). Reclamation is generally done in the winter to take advantage of frost in the borrow areas and also the placement areas. The lumps and frozen blocks are broken down and spread/smoothed the following spring.

To date, there have been over 7000 hectares of mine land in the oil sands that have been reclaimed; some of the reclamation is over 40 years old. For the most part, lands are reclaimed within about a year of being finished by mining and tailings operations. The toes of dumps and the dykes are typically reclaimed progressively as each bench becomes available.

Reclamation of tailings areas is more challenging than the reclaiming of dumps in some ways, easier in others. Reclaiming tailings sand slopes is relatively straightforward, except that blowing sand from the beaches can cover reclamation material, and any defects in the surface water drainage leads to erosion of the cover soils and exposure of the highly erodible tailings sand below, requiring maintenance. Tailings beaches above the water table are easy to reclaim. Those with the water table at surface can liquefy under cyclic loading of large equipment, causing equipment to be mired, waterlogging and salinization of newly placed reclamation soils.

Pond reclamation is especially challenging where the areas are underlain by soft tailings. Ideally, the soft tailings are both strong enough and dense enough to be capped hydraulically by beaching with a tailings line (and the planning allows enough room and tailings volume to put a tailings sand cap on (typically averaging 5 m thick). In some cases, the reclamation is done with geogrid, thin lifts of granular material and very small equipment resulting in higher risk, and even higher cost.

Vegetation depends on the land uses and substrates as described below.

Reclamation certification involves assessing the reclamation, preparing and submitting an application for reclamation certification, a review and a field inspection. Requirements for certification are evolving rapidly at present.

There are dozens of technologies and techniques involved with terrestrial, wetland, and water capping types of reclamation, but these are not the focus of the present study. It was judged as sufficient to describe three broad categories of reclamation (terrestrial, wetland, and water capping) to cover most reclamation technologies. Where there were third-party technologies submitted, these were included in the master technology list.

5.1.1 Terrestrial Reclamation

About 50 to 70% of each landscape will be reclaimed to terrestrial land uses (See Figures 5-1 and 5-2). Terrestrial reclamation involves placement of 50 to 120 cm of reclamation material, typically in two layers, (a secondary material [e.g., glacial till], overlain by a peat-mineral mix salvaged ahead of mining), sometimes direct hauled, sometimes from a stockpile. The areas
are first planted to barley (which survives one season and adds organics, structure and some erosion control to the newly placed soils), then planted with a mix of native trees and shrubs according to the expected moisture conditions. Most of the tailings dykes and upper beaches are reclaimed to a terrestrial landscape.

Two guides to terrestrial reclamation in the oil sands are:


![Figure 5-2: Terrestrial Oil Sands Reclamation](image)

### 5.1.2 Wetland Reclamation

About 20 to 40% of each landscape will be reclaimed to wetlands. The majority of these will be on tailings plateaus where there is upward discharging seepage water and very low topographic gradients (usually less than 0.3%). Wetlands may be of several types; fens, bogs, marshes, open water wetlands, and also littoral zones around end pit lakes.

Designs for wetlands and their watersheds revolve around the water balance and water levels, water quality, and initial vegetation.

Reclamation usually involves placement of about 30 cm of peat in the base of the wetland, and planting with aquatic vegetation. Marsh reclamation is reasonably advanced and there are two large fen wetland research instrumented watersheds being constructed. One of the questions being addressed is the amount of tailings water released to these wetlands, and the quality of the water. Extensive fens are likely to develop, but these may require water that has lower total dissolved solids (TDS) and lower sodium than is presently used as recycle water. Research is ongoing.

As stated above, wetland reclamation is only covered in its simplistic terms here. There is millions of dollars of ongoing wetland research each year, numerous commercial scale marshes
and several prototype fens. Technology developed for these wetland already spans a wide range of substrates and chemistries.

5.1.3 Water Capping

Water capping involves the creation of end pit lakes, all of which are water filled mined out pits, some of which will have soft tailings substrates, and virtually all will receive process affected waters from their watersheds for centuries after mine closure.

In general, the work involves preparation of the watershed and the riparian and future littoral zones around the lake, deposition of tailings in the pit, and capping with water. A new end pit lake design guide is being developed by CEMA and is due out in 2012. About 5 to 10% of the reclaimed landscape will be occupied by end pit lakes; about 30 end pit lakes are planned for the regional landscape. There remain many uncertainties in the design and performance of end pit lakes, and there is extensive research and development underway, particularly by Syncrude and CEMA.

Water quality is central to end pit lake performance, both any consolidation water from tailings within the lake, as well as consolidation and dyke seepage water from other tailings landforms in the lake’s watershed. Water treatment is likely required until the lake water quality is suitable for discharge to natural receiving waters (perhaps 20 to 50 years after filling). It is expected that lakes and wetlands will be efficient, passive bioreactors for naphthenic acids in tailings consolidation and seepage and water.

There are mature reclamation technologies available to treat trafficable surfaces and prototype efforts for water capping for fluid tailings (end pit lake technology) are ongoing. While not the focus of this study, there remain research and development opportunities to improve the performance and develop new reclamation techniques. This work is already being carried out by industry, regulators, academics and through multiparty groups like the Cumulative Effects Management Association (CEMA).

5.2 Water Treatment

Little water treatment is usually required for use of water in the extraction plant. Caustic may be used to soften the water as part of the extraction process. Water treatment for various uses by each of the extraction and refinery operations is common.

No process affected water is discharged to the environment; each operation works on a closed circuit basis. Eventually the landscapes will be reconnected with the environment and water treatment, to reduce the salinity and/or toxicity due to naphthenic acids, will be required. Passive treatment with end pit lakes and wetland is planned, with active water treatment as a short-term contingency.

Table 5-1 provides a summary of water treatment options.

There are a wide variety of mature water treatment technologies available within the oil sands and from non-oil sands industries worldwide. In general, the development of water treatment
applications for the oil sands industry are not specific to any one tailings technology. Technologies can be adapted to oil sands process water relatively rapidly as needed. A roadmap for development of water treatment technologies is largely beyond the scope of the present project. If there were discharge water quality guidelines for the oil sands, there would be an early opportunity to develop passive and active water treatment technologies for discharging process-affected water back to the environment. This would reduce engineered containment requirement for tailings ponds, and allow for more progressive reclamation to occur.

5.3 Moving forward

There are many mature commercial technologies available for both reclamation and water treatment that span a wide range of water qualities, quantities, and substrates and can be easily adapted to new tailings technologies. The initial plan to evaluate reclamation and water treatment technologies should be revisited. Instead an alternative approach that involves offering broader recommendations to existing programs should be considered.
<table>
<thead>
<tr>
<th>Description</th>
<th>Technologies</th>
<th>Target</th>
<th>State of practice in oil sands</th>
<th>State of practice in other industries</th>
<th>Potential use in oil sands</th>
<th>Benefits for use in oil sands</th>
<th>Limitations for use in oil sands</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oil and Grease Removal</strong></td>
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<td>Fats, oils and waxes are commonly termed oil and grease, and include kerosene and other petrochemical and hydrocarbon compounds (Metcalf and Eddy, 2008). Oil and grease must be removed during treatment before downstream processes that can be adversely affected by their presence such as activated carbon and some membrane processes; as well as before discharge, as they can interfere with biological life and create unsightly films.</td>
<td>T-441 API Separator T-442 Walnut Shell Filters T-443 Continuous Precipitation Separators T-447 Induced Air Flotation</td>
<td>Fats, oils, waxes</td>
<td>API Separators have been used in oil sands upgrading facilities. Walnut Shell Filters, Continuous Precipitation Separators, and Induced Air Flotation are all used extensively in SAGD operations in the Oil sands industry.</td>
<td>Well understood process with widespread commercial use in domestic water and wastewater treatment. Many suppliers with patented and proprietary materials and systems.</td>
<td>Removing hydrocarbons from influent stream to water treatment to prevent damage or adverse effects on downstream processes.</td>
<td>Commercial grade technology for use in Oil sands industry. Low level of supervision and maintenance of processes.</td>
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<tr>
<td><strong>Biological Treatment</strong></td>
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<td>Suspended Growth water treatment technologies utilize processes where the microorganisms responsible for the degradation and reduction of undesirable constituents are maintained in suspension in the liquid (Metcalf and Eddy, 2008). Processes may be aerobic, anoxic, or anaerobic.</td>
<td>T-460 Activated Sludge T-462 Nitification and Denitification T-457 Anaerobic Digestion</td>
<td>BOD, COD, Large Organics, TSS (if followed by Sedimentation), Ammonia, Nitrogen, Sulphur</td>
<td>No current or historical use in oil sands operations as a complete process. Some unit processes such as PACT have been used as pre-treatment for other processes.</td>
<td>Well understood technologies with commercial use in domestic and industrial water and wastewater treatment, including the petrochemical processing and pulp and paper industries. Nitification, denitification, and other biological processes may be used in tandem with conventional activated sludge processes for enhanced biological nutrient removal. PAC may also be added to foster higher removals of inorganics from within aeration chamber.</td>
<td>Regulatory compliance of BOD / COD for release of effluent</td>
<td>Scale of effluent water from oil sands operations is largely comparable to those of medium-sized municipalities which efficiently operate facilities using similar technologies.</td>
<td>Variance in influent temperature (especially cold) may decrease removal and efficiency.</td>
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<tr>
<td>Attached Growth / Fixed-Film water treatment utilizes processes in which microorganisms responsible for the degradation and reduction of undesirable constituents are attached to an inert medium such as rocks, slag or specially-designed synthetic materials (Metcalf and Eddy 2008). These inert media may also provide additional removal as filtration. Processes may be aerobic, anoxic, or anaerobic. Usually followed by Sedimentation.</td>
<td>T-143 Percolating (Trickling) Filter T-459 Rotating Biological Contactors (RBC) T-466 Microbial Beds T-468 Membrane Bioreactors (MBR) and Sequencing Bath Reactors (SBR) T-469 Anaerobic Fixed-Film</td>
<td>BOD, COD, Large Organics, TSS, Ammonia, Nitrogen, Metals</td>
<td>No current or historical use in oil sands operations.</td>
<td>Percolating filter, RBC and MBR well understood technologies with commercial use in domestic water and wastewater treatment. Practical application generally reliant on pilot studies to characterize removal rates and efficiencies. Many suppliers with patented and proprietary materials and systems. Microbial beds an observable natural phenomenon with potential use in marine remediation.</td>
<td>Regulatory compliance of BOD/COD for release of effluent</td>
<td>Cold weather climates adversely affect removal rates and efficiencies (especially percolating filters); would require heating / insulating.</td>
<td>Flow rates may be too large or effective wholesale use.</td>
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<tr>
<td>Description</td>
<td>Technologies</td>
<td>Target</td>
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<td>Lagoon Processes are processes which take place within ponds or lagoons with various aspect ratios and depths (Metcalf and Eddy, 2008).</td>
<td>T-149 Metal Removal by Micro Algae</td>
<td>As, Ba, Co, Ni</td>
<td>Field level test at two existing tailings ponds in Oil sands operations.</td>
<td>Used in some wastewater treatment and remediation applications.</td>
<td>Regulatory Compliance of metals</td>
<td>Algae consortium developed from indigenous population. Process utilizes existing tailings ponds.</td>
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<td>Coagulation and Flocculation are the adding of floc-forming chemicals to a water to form with unsettled floc and slow-settling suspended solids to produce a rapid-settling floc (Reynolds and Richards, 1996). Coagulation refers to the addition and rapid mixing of a coagulant, and the initial aggregation of suspended particles. Flocculation refers to the gentle agitation to further aggregate the colloids to form settleable flocs.</td>
<td>T-450 Solids Contact Clarifier Reactor Clarifiers T-477 Adsorption Clarifier T-447 Induced Air Potation</td>
<td>TSS</td>
<td>No known use of Adsorption Clarifier in Tailings water.</td>
<td>Well understood process with widespread commercial use in domestic water and wastewater treatment. Many suppliers with patented and proprietary materials and systems.</td>
<td>Primary Treatment of oil sands wastewaters prior to sedimentation.</td>
<td>Coagulant reagents non-recoverable.</td>
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<td>Sedimentation is a solid-liquid separation using gravitational settling to remove suspended solids (Reynolds and Richards, 1996). Sedimentation usually follows other processes which promote settling (Coagulation and Flocculation) or increase TSS (Suspended Growth). Sedimentation basins may also include materials or structures such as maintenance of a solids layer or a LaMella Separator to enhance settlement behaviour.</td>
<td>T-450 Solids Contact Clarifier</td>
<td>TSS</td>
<td>Epuramat currently undergoing research for Oil sands applications.</td>
<td>Well understood process with widespread commercial use in domestic water and wastewater treatment as well as industrial wastewater treatment. Many suppliers with patented and proprietary materials and systems.</td>
<td>Improving removal of TSS before and after secondary treatment. Drinking water (from river).</td>
<td>Oil sands lease lands sufficiently large.</td>
<td>Epuramat technology flow rates too small for Oil sands water treatment.</td>
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<td>Granular Filtration is a solid-liquid separation where the liquid passes through a porous medium to remove as much fine suspended solids as possible (Reynolds and Richards, 1996). Sand and other natural granular media may be used along with other synthetic or adsorbent media.</td>
<td>T-464 Carbon Adsorption (GAC) T-488 Green Sand Filtration T-431 Organophyllic Clay (Celco)</td>
<td>TSS, Large Organics</td>
<td>No current or historical use of Green Sand in oil sands operations.</td>
<td>Well understood process with widespread commercial use in domestic water and wastewater treatment.</td>
<td>Drinking water (from river).</td>
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**Physical and Chemical Treatment**
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<tr>
<td>Adsorption</td>
<td>T-461 Powdered Activated Carbon (PAC) T-464 Carbon Adsorption (GAC) T-477 Adsorption Clarifier T-431 Organophyllic Clay (Celco)</td>
<td>BOD, COD, TOC</td>
<td>No current or historical use in Oil sands operations.</td>
<td>Well understood process with widespread commercial use in domestic water and wastewater treatment. GAC is commonly combined with other granular media in Granular Filtration to enhance filter removal rates. Activated carbon commonly used in air pollution control in heavy-emitting industries like coal-fired power generation. Recommended in a pre-feasibility study of industrial wastewater treatment and reuse for the Industrial Heartland area near Edmonton, AB where oil sands upgrading wastewater is to be handled.</td>
<td>Regulatory compliance of BOD/COD for release of effluent. Drinking water (from river).</td>
<td>Better tolerance of high concentrations of refractory organics. High removal rates of complex industrial wastewater BOD and COD. Activated carbon may be used or required to complement other treatment technologies as pre-treatment.</td>
<td>Some carbon may be captured and reactivated.</td>
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<td>Conventional/Advanced Oxidation Processes (AOP) are used to oxidize complex organics that are difficult to biodegrade (Metcalf and Eddy, 2008). In many cases, partial oxidation is sufficient to convert specific compounds to be more easily biodegradable or less toxic. AOPs typically involve the generation and use of the hydroxyl free radical (HO) as a strong oxidant (Metcalf and Eddy, 2008), although other oxidants may be used such as oxygen, ozone or chlorine.</td>
<td>T-454 Oxidation/Reduction (Conventional) Oxidants: Chlorine, Chlorine dioxide, Potassium permanganate T-455 Advanced Oxidation Oxidant: HO· from UV/peroxide, UV/Ozone, Ozone/peroxide T-488 Green Sand Filtration</td>
<td>TOC, Refractory Organics, VOC, Naphthenic Acids</td>
<td>No current or historical use in Oil sands industry.</td>
<td>Fully commercially developed technology in domestic water and wastewater treatment. Many suppliers with patented and proprietary materials and systems.</td>
<td>Oxidizing organics prior to RO. Treatment to release quality.</td>
<td>Energy intensive. Peroxide processes potentially explosive. Must address EHS impact of residual peroxide.</td>
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<td>Precipitation uses relative insolubilities of target constituents to remove them from water. Precipitation is induced by chemical addition, with precipitates falling out of solution. Water softening is commonly accomplished with precipitation through precipitation of Calcium carbonate and Magnesium hydroxide.</td>
<td>T-453 Precipitation T-481 Softening</td>
<td>Various Metals, Ca, Mg</td>
<td>Softening widely used in SAGD operations in oil sands industry with pilot studies on tailings water. No current use or history of use of other precipitation in oil sands industry.</td>
<td>Fully commercially developed technology in domestic water and wastewater treatment.</td>
<td>Water softening.</td>
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<td>pH Modification is a process whereby the pH of a water is altered by the addition of a mineral acid. Usually used as a pre-treatment process to bring pH to the near-neutral range (6.5-7.5). This may prevent scale-forming precipitates such as Calcium carbonate from building up.</td>
<td>pH Modification</td>
<td>pH</td>
<td>Widely practiced in Oil sands operations water treatment.</td>
<td>Fully commercially developed technology in wastewater treatment as well as industrial systems.</td>
<td>pH control. Scale prevention.</td>
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<tr>
<td>Freeze Separation is a demineralization process where high ionic strength water is frozen and subsequently melted. The process takes advantage of the property of salts migrating away from zones of freezing.</td>
<td>T-295 Freeze Separation</td>
<td>Salts</td>
<td>No current of historical use in oil sands applications.</td>
<td>Salt removal. Water softening.</td>
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<tr>
<td>Magnetohydrodynamics</td>
<td>T-261 Magnetic Water Treatment (MWT) Clear Sky Technology 428 Zeta Potential Alteration (EDGE Process) by Griswold Water Systems</td>
<td>Metals, Various Ions N/A</td>
<td>Currently undergoing research for use in oil sands tailings water. No current or historical use in oil sands operations.</td>
<td>Used commercially in residential, and industrial maintenance to prevent scale build-up in pipes. Used in conjunction with Air Flotation units to maximize coagulant and polymer interaction with ions of interest.</td>
<td>Scale prevention, pH control; can maintain pH~7.1. Maximize TSS and Oil and Grease removal in Air Flotation units.</td>
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<tr>
<td>Disinfection</td>
<td>T-484 Chlorine Disinfection T-487 Ultraviolet (UV) Irradiation</td>
<td>Bacteria, Protozoa, Viruses UV</td>
<td>Bench scale tests of chlorine disinfection on tailings water. UV utilized for drinking water and boiler feed water in Oil sands.</td>
<td>Both fully commercially developed technologies in domestic water and wastewater treatment. Chlorine disinfection may use chlorine gas or combined chlorine such as chloroamines.</td>
<td>Boiler feed water, Drinking water (from river).</td>
<td>Chlorination produces chlorine residuals which provide additional contact time after initial chlorination.</td>
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</table>

Disinfection is the destruction or inactivation of pathogenic microorganisms. Disinfection does not pertain to the destruction of these microorganisms existing in the spore state, which is known as sterilization (Reynolds and Richards, 1996).

Water Treatment Solids Handling refers to processes designed to alter or dispose of constituents removed from water during treatment (Metcalf and Eddy, 2008). These constituents include screenings, grit, scum, solids and biosolids. Due to the highly active and reactive nature of some of these removed constituents, processing or deactivation may be required before ultimate disposal.
6. DEVELOPMENT OF TAILINGS TECHNOLOGIES

Tailings technology development has been a significant activity in the oil sands industry since the late 1960s. This section provides an overview of tailings technology development and the status of technologies in the development stage. Table 6-1 provides a list of pilots and prototypes for tailings and related technologies.

Tailings technology development in the oil sands to date has involved individual companies and consortiums of companies, often working through the Canadian Oil Sands Network for Research and Development (CONRAD), or with universities, consultants, and provincial and federal government laboratories and agencies. Tailings and tailings research and development are mature activities within the oil sands.

Each of the operators has individuals dedicated to oil sands tailings research and development. These individuals are responsible for assessing new technologies, attending conferences, and identifying technologies worth following up at a research level. Teams within the company, or through collaborative groups, meet periodically to assess various technologies to set research and development priorities.

Every few years, as an internal exercise, or in preparation for submission of a new approval, technologies are screened against operating, environmental, technology, and cost objectives, and the highest ranking technologies are selected for further development or commercialization. This screening process takes up to about one year and involves creating conceptual mine and tailings plans, complete with realistic cost estimates and prediction of operational, geotechnical, and environmental performance, using the latest information.

Promising technologies are often piloted, and if the pilot is successful, the technology is assessed for commercial application, including regulatory approval. Piloting activities at this point involve detailed geo-environmental assessment, including water quality assessment, greenhouse and field reclamation studies, and conceptual design of commercial implementation. Stakeholder and regulatory consultation specific to the technology is required. Research and development into specific aspects of the technology continue.

If the decision is made to commercialize a technology, an application for amendment of the operators EPEA approval is made, and tailings plans and budgets (and often mine plans) are changed to reflect the realities of the new technology.

Sometimes a large prototype of the technology is done in the year before the technology is employed. Other times, the first train of the technology (there are often several trains for commercial operation) serves as the prototype, with learnings from design, construction, and operation of the first train used to improve the designs of future trains.

Typically several years of research are required to evaluate a new technology and provide realistic design / planning criteria for scale up. Piloting takes an additional one to two years. Design, preparation of a regulatory application and gaining approval typically involves several more years. Construction adds one to three years for the first trains, and additional trains are
added in subsequent years. It often takes five to ten years or more of commercial implementation to bring the technology to its full potential. In the end, from the initial bench tests to full commercial steady-state implementation, it is an 8 to 15 year process, with investments in the range of several hundred million dollars to greater than a billion dollars, involving hundreds of people.

Commercial implementation involves strict project management, usually involving the “gate” system. More recently, pilots and prototypes, which often cost millions to tens of millions of dollars, are run as formal projects using a modified R&D gate system that reduces risks but also constrains innovation and change. At start up, new operations tend to use a combination of old and new technology. While there are major opportunities, employing unprecedented tailings technologies at start-up carries very high risks. Operators often choose to implement well-proven commercial technologies at start-up of a new mine and then bring in new technology or technological advances over time.

Technology attrition rates are high. Typically only one in ten technologies (or less) tested at the bench scale reach the development scale, and about one in three in the development process reach full-scale commercial production. A high percentage of technologies that reach commercial scale production are sidelined due to scaling issues, changing conditions, or competing technologies.

Recently projects have been fast tracked, going from bench scale to partial commercial implementation over a five-year process. Fast tracking involves additional costs and risks, and may extend the commercial implementation / commissioning period. Risks include the technology being dropped or significantly modified and off-spec deposits needing to be remediated.

Much or most of the technical innovation does not result from bottom up research, but instead comes from the designing of components for commercial systems where new, enabling technology is needed. But by far most of the innovation comes from continuous improvement and additions to existing commercial systems, new designs for components or new components to improve efficiency, reduce cost, or improve the product. Thus much of the tailings systems in place today are evolutions in technology, rather than revolutions. A central tension in the operation is the dividing efforts between incremental improvements and wholesale changes.

### 6.1 Upscaling

As mentioned previously, the scaling of technologies is always an issue, and oil sands tailings is no exception. Developing technologies to commercialization requires progressive testing at larger scales (upscaleing) as many processes that work well under laboratory conditions do not work well under commercial conditions. The range of scales is very large (see Figure 6-1). Some of the changes in scale up include:

- Moving from batch to continuous processes.
- Difficulty in retrofitting to an existing operation (for example, conversion from a water based extraction process to a different process).
• Variability in feed stocks (for example, the wide range in flow rates, solids contents, fines contents, bitumen contents, water chemistry, and to some extent clay mineralogy) for processing tailings.

• Difficulty in dealing with variability in output (especially off-spec tailings).

• Competing objectives between extraction / production and tailings goals, especially where the processes are closely linked.

• Difficulties in seasonal operation (especially winter) and where weather fluctuations (rain, wind, snow) interfere with tailings processes.

• Situations where the technology is too complex to be operated reliably.

• Excessive capital or operating costs.

• Environmental concerns or other unintended consequences.

Figure 6-1: Scaling in Tailings R&D

Of those technologies that make it through to pilot scale, the most difficult issues usually relate to variability in the feed, and the infrastructure and cost required to deal with off-spec tailings (which can require a similar sized, separate tailings system to manage). There are, however, methods to deal with both of these issues (pre-processing of the tailings to reduce variability, tighter controls on both inputs to and outputs of various tailings processes, and selecting a technology with less sensitivity to some of the input parameters).
6.2 Oil Sands Pilots and Prototypes

A high percentage of field trials are unsuccessful. The issue is not that the technology does not prove out, but that the equipment or field conditions do not work well enough to properly assess the technology. Critical elements for a successful pilot include the following:

- Clearly defined objectives and goals.
- Dedicated, 100% onsite technical champion responsible for the successful outcome, surrounded by a good technical team.
- A good project manager, expert operators, ability to expedite repairs and changes.
- Well-designed and constructed facilities, good sampling and instrumentation locations, a good operating system, and good sampling procedures designed around a robust mass balance.
- A reliable source of tailings feed (constant, consistent properties) with an alternative location for disposal of off-spec material.
- On-site laboratory with fast turnaround times.
- Good data management.
- Enough staff to run and sample the pilot and produce results on a daily basis (this should not be left to the end).
- Dedication to write a timely and complete report that will stand the test of time.

Table 6-1 provides a list of prototype and pilot trials conducted by the oil sands industry over the past 30 years.
<table>
<thead>
<tr>
<th>Technology</th>
<th>Pilot / prototype company / date / scale of test</th>
<th>Result of pilot</th>
<th>Claim for tailings</th>
<th>Fate of technology</th>
<th>What would it take to make the technology interesting again?</th>
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<tr>
<td>Zero Fine Tailings Extraction (T-527)</td>
<td>Syncrude Research 1992, 1993 2.5 tph</td>
<td>Successful pilot.</td>
<td>Very high fines capture without chemical amendment.</td>
<td>On hold, probably as it seems counter-intuitive to introduce fines into extraction.</td>
<td>Revisit with current extraction and tailings understanding.</td>
</tr>
<tr>
<td>OSLO Cold Water Extraction (T-527)</td>
<td>OSLO’s Lease 41 1988 – 1990</td>
<td>Successful pilot demonstrated similar extraction as CHWE and better influence on fine tails.</td>
<td>Less clay dispersion, higher beach capture, faster settling of fines.</td>
<td>Evolved into LEE (T-527)</td>
<td>N/A</td>
</tr>
<tr>
<td>OSLO Hot Water Extraction (T-527)</td>
<td>Imperial Commercial Demo</td>
<td>Successful pilot; demonstrated similar extraction as CHWE and better influence on fine tails.</td>
<td>Enhanced settling and strength characteristics of fine tails.</td>
<td>Halted; proponents concentrated on understanding tailings properties rather than technology implementation.</td>
<td>Better economics to retrofit current operations.</td>
</tr>
<tr>
<td>Gulf/solid RTR (Aqueous Extraction) (T-007)</td>
<td>Suncor 1980 15 tph</td>
<td>Successful pilot</td>
<td>Less clay dispersion, recovery and reuse of process water, no tailings pond.</td>
<td>Halted as other extraction technologies use lower process temperatures and make more efficient use of cyclones.</td>
<td>Improvement of hot water loss and waste volumes.</td>
</tr>
<tr>
<td>Dravo Process (Solvent Extraction) (T-186)</td>
<td>Silver Bullet 8 tph</td>
<td>Unknown</td>
<td>Production of damp tailings suitable for immediate back-filling of mines.</td>
<td>On hold, solvent based extraction methods are being re-examined through COSI at the U of A with Imperial.</td>
<td>Ore sizing efficiency (25 mm grains) and confident solvent recovery from tailings.</td>
</tr>
<tr>
<td>SESA (T-186)</td>
<td>Silver Bullet 2 tph</td>
<td>Unknown</td>
<td>Production of a solid tailings.</td>
<td>Presently halted due to trucking / conveying cost, extraction cost, and GHG.</td>
<td>Better economics. New dry tailings paradigm.</td>
</tr>
<tr>
<td>AOSTRA Taciuk Process (Retort) (T-024)</td>
<td>Silver Bullet 5 tph</td>
<td>Successful technology, dry tailings.</td>
<td>Production of dry tailings.</td>
<td>Presently halted due to trucking / conveying cost, extraction cost, and GHG.</td>
<td>Better economics. New dry tailings paradigm.</td>
</tr>
<tr>
<td>CT (T-059)</td>
<td>Suncrude 1994 100,000 m³, 10 mM³</td>
<td>Successful, produced non-segregating tailings.</td>
<td>Produce a non-segregating mixture; target SFR between 3:1 and 6:1.</td>
<td>Presently operating at 12,000 tph, full scale operations.</td>
<td>N/A</td>
</tr>
<tr>
<td>MFT Spiking (T-060)</td>
<td>Syncrude 1993, 1995, 1996, 1997 20,000 usgam</td>
<td>Successful pilot, applied as dyke construction technology.</td>
<td>Increased fines capture in tailings pores without too much loss in geotechnical performance.</td>
<td>Shelved due to poor fines capture and significant changes to permeability of deposit,</td>
<td>Would require someone to run it commercially and prove it works.</td>
</tr>
<tr>
<td>Super CT (T-197)</td>
<td>Shell Albian Test Facility 2009</td>
<td>Unknown</td>
<td>Produce a non-segregating mixture with higher solids content than CT; Target SFR &gt;3:1,</td>
<td>Halted due to consistency of product, high level of operations required and mixing difficulty,</td>
<td>Better process controls and reliable pumping systems.</td>
</tr>
<tr>
<td>Lime Tailings (T-059)</td>
<td>Syncrude 1996</td>
<td>Worked, but high pH and less efficient that CT with Gypsum.</td>
<td>Produce non-segregating deposit.</td>
<td>Lost to CT (T-059) with gypsum due to economics, release water quality, soft deposits and low beach angles.</td>
<td>Super-ceded</td>
</tr>
<tr>
<td>Technology</td>
<td>Pilot / prototype company / date / scale of test</td>
<td>Result of pilot</td>
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<td>What would it take to make the technology interesting again?</td>
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<td><strong>Conventional Thickeners</strong> (T-207)</td>
<td>CONRAD Syncrude ASB 10 m pilots 2000-2004, 2008</td>
<td>Successful</td>
<td>Thickening process to aggregate fines and increase tailings solids contents.</td>
<td>Not pursued due to better performance from high compression thickeners and other technology options at the time, particularly centrifuge.</td>
<td>Better flocculants.</td>
</tr>
<tr>
<td><strong>In-line Thickening</strong> (T-044)</td>
<td>Suncor 2007</td>
<td>Successful</td>
<td>Tailings coagulant thickening that does not require a process vessel. Thickened solids contents range from 30 to 50%.</td>
<td>Commercial at Suncor.</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>In-line Thickening</strong> (T-044)</td>
<td>Syncrude SWISS 2005 400 m³/hr cyclone overflow</td>
<td>Successful</td>
<td>Tailings coagulant thickening that does not require a process vessel. Thickened solids contents range from 30 to 50%.</td>
<td>Successful, but high polymer cost.</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Centrifuge MFT</strong> (T-069)</td>
<td>Syncrude MLSB 2007, 2008</td>
<td>Successful using two nominal 400-mm diametral machines and one nominal 355 mm diametral machines</td>
<td>Reduce legacy MFT volumes.</td>
<td>Planned for a commercial trial in 2011.</td>
<td>TBA</td>
</tr>
<tr>
<td><strong>CT Underdrain</strong> (T-188)</td>
<td>Syncrude EIP 2003</td>
<td>Unsuccessful, difficulties in operating pumping system, mixed performance.</td>
<td>Improve consolidation of tailings through double drainage. Increases solids content and strength.</td>
<td>Commercially operated at Suncor TRO. Found macro fractures in deposit can feed under-drain. Working technology.</td>
<td>Wide use for deposition technologies.</td>
</tr>
<tr>
<td><strong>Thin Layer MFT Evaporative Drying</strong> (T-040)</td>
<td>Syncrude MSLB 1996</td>
<td>Successful</td>
<td>Increased dewatering rates upon deposition in thin (20 – 50 cm) lifts.</td>
<td>Not pursued due to investigations of other proponent technologies.</td>
<td>Better lift sequencing and deposit consistency.</td>
</tr>
<tr>
<td></td>
<td>Suncor Pond 1 2008</td>
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<td>Implemented at commercial scale [as TRO], 2.9 MT of solids dried (2010).</td>
<td>N/A</td>
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<td>Suncor Pond 8A 2009</td>
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<td><strong>Thin Layer MFT Freeze Thaw</strong> (T-037)</td>
<td>Syncrude Pond 2A 1992 8051 m² area, 13,600 m³ tailings pumped</td>
<td>Successful demonstrating a 0.5 m³ volume reduction for every 1m³ placed. Found this method becomes less effective with increasing solids content.</td>
<td>Increase of in-situ solids content (35 to 65%, [Beier, et al. 2009]) via regular freeze-thaw cycles.</td>
<td>Used to assist dewatering during ILLT field trails. Suncor, Shell and Syncrude are currently re-evaluating with MFT drying and centrifuge technologies.</td>
<td>Finding appropriate synergistic technologies.</td>
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<td></td>
<td>Syncrude Pond 2B 1992 7152 m² area, 12,600 m³ tailings pumped</td>
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<td>Syncrude WIP Field Trial 1996</td>
<td>Mildly successful</td>
<td>Increase solids content and consolidation rates.</td>
<td>Judged as expensive (at the time), difficult to operate, and requiring large areas.</td>
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<tr>
<td><strong>Accelerated Dewatering</strong> (T-032)</td>
<td>Syncrude MSLB 2009-2011</td>
<td>Under review</td>
<td>Increase of the tailings solids content and shear strength.</td>
<td>Demonstrates promise; has a potential to be useful with other technologies, need to assess what should be done with remaining water.</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Wick Drains (Pond 5)</strong> (T-090)</td>
<td>Suncor Pond 5 2008</td>
<td>Successful showing 0.002 m³/day dewatering rates.</td>
<td>Increase in-situ solids content via increased dewatering and consolidation.</td>
<td>Being tested and installed for 2010-2011 trails under a coke cap.</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Beach Loading Field Trial</strong> (T-513)</td>
<td>Syncrude ASB 2005-2011</td>
<td>Successful; densified beach sand such that a second lift was added.</td>
<td>Increased consolidation of loose BBW sand</td>
<td>Used recently at Aurora. Other densification methods are preferred for more recent sites.</td>
<td>Where needed as a contingency.</td>
</tr>
<tr>
<td><strong>MFT Cement</strong> (T-242)</td>
<td>Suncor Pond 1 2008</td>
<td>Unsuccessful</td>
<td>Greatly improve MFT shear strength.</td>
<td>Discontinued due to high volumes of fly ash required, costs, inconsistencies of deposit.</td>
<td>Better economics.</td>
</tr>
<tr>
<td>Technology</td>
<td>Pilot / prototype company / date / scale of test</td>
<td>Result of pilot</td>
<td>Claim for tailings</td>
<td>Fate of technology</td>
<td>What would it take to make the technology interesting again?</td>
</tr>
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</tr>
<tr>
<td>CO2 Injection for TT (T-268)</td>
<td>CNRL / Conrad Syncrude ASB 2007, 2011</td>
<td>Successful</td>
<td>Accelerate clarification along lines.</td>
<td>Being commercialized at CNRL.</td>
<td>N/A</td>
</tr>
<tr>
<td>MFT / Kc Mixing / Poudlering (T-062)</td>
<td>Syncrude 30 Dump 1989 and 1990</td>
<td>Successful</td>
<td>MFT fines capture and shear strength increases.</td>
<td>Not pursued given other tailings management options under consideration at the time.</td>
<td>Better mixing mechanisms, more consistency from deposit.</td>
</tr>
<tr>
<td>Suncor Pond 1 Plant 4 Soft Cap (T-107)</td>
<td>Suncor Pond 1 10 ha</td>
<td>Successful</td>
<td>Provides a reclaimable surface for storage facilities.</td>
<td>Commercial technology.</td>
<td>N/A</td>
</tr>
<tr>
<td>Hydraulic Sand Capping of CT (T-107)</td>
<td>Syncrude CT Prototype 1998 20 ha</td>
<td>Successful</td>
<td>Provides a reclaimable surface for storage facilities.</td>
<td>Implemented commercially at the east in pit.</td>
<td>N/A</td>
</tr>
<tr>
<td>Hydraulic Coke Capping of CT (T-107)</td>
<td>Suncor Experimental cell 2000</td>
<td>Successful</td>
<td>Provides a reclaimable surface for storage facilities.</td>
<td>On hold, similar costs to mechanical capping.</td>
<td>N/A</td>
</tr>
<tr>
<td>Mechanical Sand Capping of CT (T-115)</td>
<td>Syncrude MLSB 1999 1000 m³</td>
<td>Successful</td>
<td>Provides a reclaimable surface for storage facilities.</td>
<td>Commercial technology.</td>
<td>N/A</td>
</tr>
<tr>
<td>Mechanical Sand Capping of CT (T-115)</td>
<td>Syncrude MLSB 2001 9ha</td>
<td>Successful</td>
<td>Provides a reclaimable surface for storage facilities.</td>
<td>Commercial technology.</td>
<td>N/A</td>
</tr>
<tr>
<td>Micro Algae Treatment (T-533)</td>
<td>Research on uptake of metals by microalgae in Tailings Pond water in-situ</td>
<td>Metals removed: • As, 45 to 50% • Ba, 67 to 70% • Co, 30 to 42% • Ni, 45 to 50%</td>
<td>Metals Removal, Reduce Toxicity.</td>
<td>No evidence of commercialization.</td>
<td>Need for metals removal for discharge.</td>
</tr>
<tr>
<td>Coke Water Treatment Pilot (T-537)</td>
<td>Syncrude MLSB 2011</td>
<td>Just starting</td>
<td>Only practical for plants with Upgrader using fluidized cokers.</td>
<td>Only practical for plants with Upgrader using fluidized cokers.</td>
<td></td>
</tr>
<tr>
<td>Polymeric Ultrafiltration (T-538)</td>
<td>Syncrude, 2001 and Suncor, 2010 for suspended solids removal as pre-treatment for RO and EDR</td>
<td>Successful</td>
<td>TSS removal from tailings water.</td>
<td>Ready for application.</td>
<td>N/A</td>
</tr>
<tr>
<td>EDR (T-494)</td>
<td>Syncrude 2001</td>
<td>Successful</td>
<td>Desalination of tailings water.</td>
<td>Ready for commercialization when required.</td>
<td>Need</td>
</tr>
<tr>
<td>Vapor Re-Compression Evaporator (T-499)</td>
<td>Syncrude, 2001</td>
<td>Successful</td>
<td>Salts Removal from EDR and RO reject.</td>
<td>Ready for implementation.</td>
<td>N/A</td>
</tr>
<tr>
<td>CT Wetland Reclamation (T-139)</td>
<td>Syncrude EIP Fen 2009 Suncor SAF Fen 2010</td>
<td>Successful</td>
<td>Reclaim DDA as a controlled wetland.</td>
<td>Commercially operating at Syncrude (~15 ha) and Suncor.</td>
<td>N/A</td>
</tr>
<tr>
<td>Technology</td>
<td>Pilot / prototype company / date / scale of test</td>
<td>Result of pilot</td>
<td>Claim for tailings</td>
<td>Fate of technology</td>
<td>What would it take to make the technology interesting again?</td>
</tr>
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</tr>
<tr>
<td>CT Terrestrial Reclamation (T-158)</td>
<td>Syncrude 1998</td>
<td>Successful</td>
<td>Reclaim tailings facility as useable land.</td>
<td>Commercially operating at Syncrude.</td>
<td>N/A</td>
</tr>
<tr>
<td>Water Capped MFT 4 ha Test Pond (T-138)</td>
<td>Syncrude</td>
<td>Successful</td>
<td>Reclaim tailings facility natural lake system which can source the Athabasca.</td>
<td>Planned for commercialization at Syncrude.</td>
<td>N/A</td>
</tr>
<tr>
<td>Syncrude Base Mine Lake Prototype (T-138)</td>
<td>Syncrude 1995-2012 800 ha</td>
<td>Trial just starting</td>
<td>Land reclaim to a natural lake system which can source the Athabasca.</td>
<td>In development.</td>
<td>Understanding of long term capabilities.</td>
</tr>
<tr>
<td>Hydraulic Hummock Construction for Water Table Control (T-425)</td>
<td>Syncrude SEP,jr 2008</td>
<td>Successful</td>
<td>Control salinization and water.</td>
<td>Commercial at Suncor Pond 1 and Syncrude EIP.</td>
<td>N/A</td>
</tr>
</tbody>
</table>
6.3 Commercial Technologies at Other Types of Mines

Various tailings technologies are employed at mines around the world, including metal mines, placer mines, coal mines, and mineral sands mines. The tailings technology selection process has drawn on technologies from these other (non-oil-sands) mines. Commercialization of tailings technologies in non-oil sands mining does not guarantee full-scale operation in oil sands mining. To provide context, Table 6-2 and 6-3 demonstrates and compares similarities and differences of tailings operations in metal versus oil sands mines.
<table>
<thead>
<tr>
<th>Category</th>
<th>Technology</th>
<th>Development</th>
<th>Use at other major industries</th>
<th>Limitation / comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mining</td>
<td>At face Mining (T-416)</td>
<td>C</td>
<td>Fully mechanized mining at face is used in the coal mining industry.</td>
<td>Impact on bitumen production rates / efficiency and tailings production systems provided any of the mobile systems go out of service.</td>
</tr>
<tr>
<td>3. Tailings</td>
<td>Paste Thickener (T-208)</td>
<td>C</td>
<td>Used in metal mines in arid areas (i.e. Alumina red muds).</td>
<td>Costly to pump paste. Valuable for water and reagent recovery.</td>
</tr>
<tr>
<td>3. Tailings</td>
<td>One Stage and Two Stage Centrifuge MFT with Floc (Solid &amp; Screen Bowl) (T-069)</td>
<td>C</td>
<td>Used for fines dewatering, i.e. oilfield industry (drill fluid) and coal industry. Used in waste sludge processing.</td>
<td>Syncrude is currently investigating the scale-up potential of centrifuge technology. Further design of commercial scale machines are required to prove scaled-up centrifuge throughput.</td>
</tr>
<tr>
<td>3. Tailings</td>
<td>Pressure Filtration (T-076)</td>
<td>C</td>
<td>Used dominantly in high value metal operations. Filtered operations are generally under 10,000 tpd. (Davies, 2010). Used in some domestic waste water treatment operations.</td>
<td>Large surface area required to support Oil Sands feeds.</td>
</tr>
<tr>
<td>3. Tailings</td>
<td>Vacuum Filtration (T-080)</td>
<td>B</td>
<td></td>
<td>Based on investigations of pressure filtration, the % solids less than 44 micron has a major influence on the rate of filtration with 8 to 12% as a limit.</td>
</tr>
<tr>
<td>3. Tailings</td>
<td>Thermal Drying (includes MFT brickmaking and other artificial drying technologies) (T-085)</td>
<td>D</td>
<td>Used dominantly in the pulp and paper, brick and tile and textiles industries.</td>
<td>Produces dry tailings, high, energy requirement consistency problems with the partially dried sludge, high investment and operating costs.</td>
</tr>
<tr>
<td>3. Tailings</td>
<td>Tailings Treatment using Electro-Flotation in Combination with Electro-Chemical Oxidation Hydro-Floc Solutions Inc. (T-248)</td>
<td>D</td>
<td>Industrial Waste water treatment (tested at 50,000 m³/day).</td>
<td>Reactors typically handle solids contents up to 30%. MFT would require dilution before treatment.</td>
</tr>
<tr>
<td>Category</td>
<td>Technology</td>
<td>Development in oil sands</td>
<td>Use at other major industries</td>
<td>Limitation / comment</td>
</tr>
<tr>
<td>------------------</td>
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</tr>
<tr>
<td>4. Deposition</td>
<td>Engineered Liner (T-405)</td>
<td>C</td>
<td>Becoming more common for tailings and mine waste. Common landfill technique.</td>
<td>Results for large scale mining areas often disappointing (leakage).</td>
</tr>
<tr>
<td>4. Deposition</td>
<td>Poldering (slop cell construction) (T-235)</td>
<td>C</td>
<td>Used in mining industries dominantly for containment of waste overburden (ARD potential).</td>
<td>Mixing in-situ to develop a homogeneous deposit is difficult.</td>
</tr>
<tr>
<td>4. Deposition</td>
<td>Cyclo-Stacking (T-099)</td>
<td>C</td>
<td>Used commonly in mineral sands.</td>
<td>Has the consequence of increasing the production of fluid fine tailings.</td>
</tr>
<tr>
<td>4. Deposition</td>
<td>Vertical Drains (wick or band drains, sand columns, electro-kinetic wicks, air injection) (T-099)</td>
<td>B</td>
<td>In use since the 1980’s in uranium, coal and metal mining for soft tailings deposits. (Brown, 2000).</td>
<td>Rate of dewatering depends on fines content of the adjacent tailings and spacing of wicks. Economics against other in-situ dewatering technologies needs to be proven.</td>
</tr>
<tr>
<td>4. Deposition</td>
<td>Accelerated Dewatering (rim-ditching) (T-032)</td>
<td>C</td>
<td>Used widely in the Florida phosphate industry. 50,000 ha have been reclaimed with this method. (Carrier 1997, 2001).</td>
<td>Oil sands effectiveness requires optimization of impoundment area, rise rate and flocculent mixing.</td>
</tr>
<tr>
<td>4. Deposition</td>
<td>Soil Cement Mixing with Additives (T-242)</td>
<td>C</td>
<td>Used as a ground improvement technology and in metals mining for coarse disposal, tailings strengthening and encapsulation of mobile metals.</td>
<td>Associated with difficult mixing techniques and additive costs.</td>
</tr>
<tr>
<td>4. Deposition</td>
<td>Vacuum Consolidation / Preloading Method Superior Geotech Consulting Ltd. (T-429)</td>
<td>-</td>
<td>Developed at the commercial scale for civil ground improvement techniques.</td>
<td>Not yet considered for Oil Sands. Economics related to high volumes of in-situ tailings need to be investigated.</td>
</tr>
<tr>
<td>Category</td>
<td>Technology</td>
<td>Development in oil sands</td>
<td>Use at other major industries</td>
<td>Limitation / comment</td>
</tr>
<tr>
<td>------------</td>
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<td>------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>4. Deposition</td>
<td>Subaqueous Capping (raining sand or coke) (T-438)</td>
<td>C</td>
<td>Environmental Industry (contaminated sediment sites).</td>
<td>Can be dredged or pumped.</td>
</tr>
<tr>
<td>4. Deposition</td>
<td>Tailings Surface Sealants to Improve Trafficability and Limit Infiltration (T-550)</td>
<td>D</td>
<td>Used widely for waste facilities with high ARD potential and dusting.</td>
<td>Requires high quantities of sealant to provide surface for oil sands facility. On site storage of sealant; winter applications unknown.</td>
</tr>
<tr>
<td>5. Water Treatment</td>
<td>Suspended Growth (T-531)</td>
<td>-</td>
<td>Used for domestic &amp; industrial waste water treatment, petrochemical processing and pulp and paper.</td>
<td>Not yet considered for Oil Sands. Variance in influent temperature may decrease removal and efficiency.</td>
</tr>
<tr>
<td>5. Water Treatment</td>
<td>Attached Growth / Fixed-Film (T-532)</td>
<td>-</td>
<td>Domestic waste water treatment.</td>
<td>Not yet considered for Oil Sands. Through-pufts need to be proven prior to commercialization of technology.</td>
</tr>
<tr>
<td>5. Water Treatment</td>
<td>Lagoon Processes (T-533)</td>
<td>C</td>
<td>Municipal waste water treatment and remediation applications.</td>
<td>Algea consortium developed from indigenous population.</td>
</tr>
<tr>
<td>5. Water Treatment</td>
<td>Coagulation and Flocculation (T-534)</td>
<td>-</td>
<td>Widely used in clarification and thickening operations.</td>
<td>Not yet considered for Oil Sands. Pilot work has shown that it is difficult to control with high chemical demand.</td>
</tr>
<tr>
<td>5. Water Treatment</td>
<td>Sedimentation (T-535)</td>
<td>-</td>
<td>Used in domestic and industrial waste water treatment.</td>
<td>Not yet considered for Oil Sands. Requires high storage for feeds related to oil sands.</td>
</tr>
<tr>
<td>5. Water Treatment</td>
<td>Adsorption (T-537)</td>
<td>C</td>
<td>Used in domestic waste water treatment and environmental remediation industries (permeable reactive barriers).</td>
<td>Tolerance of high concentrations of refractory organics. Operating cost for makeup, disposal and/or reactivation/reuse is high.</td>
</tr>
<tr>
<td>5. Water Treatment</td>
<td>Membrane Processes (T-538)</td>
<td>C</td>
<td>Widely used in waste water treatment industries.</td>
<td>Leading choice for desalination of tailings water.</td>
</tr>
<tr>
<td>5. Water Treatment</td>
<td>Conventional / Advanced Oxidation Processes (AOP) (T-539)</td>
<td>C</td>
<td>Used in domestic waste water treatment.</td>
<td>Could remove toxicity (naphthenic acids) but can be energy Intensive.</td>
</tr>
<tr>
<td>Category</td>
<td>Technology</td>
<td>Development in oil sands</td>
<td>Use at other major industries</td>
<td>Limitation / comment</td>
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</tr>
<tr>
<td>5. Water</td>
<td>Ion Exchange (T-540)</td>
<td>C</td>
<td>Used in domestic waste water treatment and occurs as a phenomenon in some SBAs.</td>
<td>Limited use for desalination due to high total dissolved solids.</td>
</tr>
<tr>
<td>Treatment</td>
<td>Precipitation (T-541)</td>
<td>C</td>
<td>Used in the domestic waste water treatment. Commercially used in SAGD operations, piloted for tailings.</td>
<td>Lowers calcium concentration in water used in extraction.</td>
</tr>
<tr>
<td></td>
<td>Distillation (T-546)</td>
<td>C</td>
<td>Used in domestic waste water treatment.</td>
<td>Expensive, energy intensive</td>
</tr>
<tr>
<td></td>
<td>Gas Stripping (T-547)</td>
<td>-</td>
<td>Used in domestic waste water treatment.</td>
<td>Not yet considered for Oil Sands. Removal of VOCS, energy intensive, requires controlled pH levels.</td>
</tr>
<tr>
<td></td>
<td>Disinfection (T-545)</td>
<td>D</td>
<td>Used in domestic waste water treatment.</td>
<td>High tailings water chlorine demand.</td>
</tr>
<tr>
<td>Element</td>
<td>Typical metal mines</td>
<td>Typical oil sands mines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dyke Configuration and Height</strong></td>
<td>Cross-valley dykes, 20 to 200m high, significant water diversions.</td>
<td>Ring dykes, 30 to 100m high. In-pit backfill (geologic containment).</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dyke Construction</strong></td>
<td>Often rock fill, sometimes with tailings sand dykes above a starter dyke.</td>
<td>Clay or lean oil sands starter dykes, upstream tailings sand construction.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Footprint Area</strong></td>
<td>20 to 250 ha; 125 ha common, often only one deposit.</td>
<td>500 to 2500 ha, typically 4 to 10 deposits.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tailings Slurry Properties</strong></td>
<td>Crushed rock, little to no clay minerals. Typically x% solids slurry with x% sand, x% fines, process affected water.</td>
<td>Natural sands and clays with residual bitumen. Typically 50% solids slurry with 80% sand, 20% fines, 1% bitumen, process affected water.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Beaching</strong></td>
<td>Partially segregating: coarse grained near the discharge, and gradually fine down the beach and into the pond.</td>
<td>High degree of segregation: coarse-grained beaches with consistent grain size, clay rich fines in the pond.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Settling / Consolidation Behaviour</strong></td>
<td>Fine tailings generally settle and consolidate within a few years, forming a surface suitable for reclamation.</td>
<td>Consolidation of fine tailings takes decades to centuries.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Trafficability</strong></td>
<td>Upper beaches are fully trafficable, lower beaches trafficable with small equipment, fines areas require special soft tailings reclamation techniques (mechanical capping with small equipment).</td>
<td>Beaches above water table trafficable with large equipment. beaches with high water tables trafficable with good frost, fine tailings not trafficable.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Porewaters</strong></td>
<td>Often high metal contents, metal leaching, acid mine drainage.</td>
<td>Elevated salts and naphthenic acids.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ease of Reclamation</strong></td>
<td>Beaches typically easy to reclaim, but often require engineered covers. Final tailings area expensive but routine to reclaim and limited in aerial extent.</td>
<td>Beaches typically easy to reclaim, soft areas difficult to reclaim, but possible at high cost.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Focus of Technology Development</strong></td>
<td>Reduced water usage / increased reagent recovery. Reduced containment requirements / risks. Covers to reduce acid mine drainage and metal leaching.</td>
<td>Reduced volumes of fluid tailings. Wetland and water capping reclamation. Reduced water usage.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.4 Moving forward with development

There have been a large number of pilots and prototypes completed over the past 30 years. Many of these technologies have been advanced to commercial development; while others have been eliminated or require further testing and assessment. The list of development stage technologies (Table 6-1) that merit advancement towards commercialization should be reviewed for their potential for advancement to the next stage.

There are 34 technologies (14 of which are water treatment) that are in commercial use outside the oil sands. There may be opportunities to adopt these methods in oil sands work. The list of technologies that are commercial at other types of mines (Table 6-2) should be screened for their potential for advancement to the next stage.
7. TECHNOLOGIES IN RESEARCH STAGE

7.1 Introduction

Taking tailings technology from research to piloting can be complex and time consuming, requiring many years and collaboration with inter-disciplinary teams. In the oil sands, it is typical for only one in ten technologies to advance from the research scale to the pilot scale. The following section provides an overview of current oil sands tailings technology research.

7.2 Tailings Technology Research

Historically in the oil sands industry, a large volume of tailings research has been conducted at many locations throughout North America, with the majority through universities, independent researchers, governmental agencies and industry. Currently much of the research is being conducted for the oil sands industry by University of Alberta (UofA), the Oil Sands Tailings Research Facility (OSTRF), the Oil Sands Research and Information Network (OSRIN), the Canadian Oil Sands Network for Research and Development (CONRAD), the Saskatchewan Research Council (SRC), CANMET, AI-EES, and a developing research initiative through Northern Alberta Insitute of Technology (NAIT).

Research on oil sands tailings technologies is used to understand the fundamental concepts of each technology, and their impact on tailings properties. These research investigations involve either a revisit of a current technology or development of an original technology. By conducting a systemic investigation of the potential technologies, this process allows for an initial screening of technologies during the developmental process.

The initial stages of research for oil sands tailings technologies include a conceptual process and preliminary testing. This stage provides an opportunity for researchers to develop new concepts for technologies based on the current gaps in development. Promising concepts can be developed as laboratory / bench scale studies, usually as a batch process, to understand the fundamental concepts associated with each technology. These studies are coupled with scientific and engineering analysis, to attempt to prove fundamental concepts. If the concept shows promise, the technology can be further developed in research for feasibility studies and larger scale tests.

Large-scale research begins defining the piloting potential of a new tailings technology. This stage involves a larger degree of consideration integrating engineering, environmental, and economic analysis. If a technology continues to show promise and can be well established at larger scales, research groups must obtain the appropriate patents and approach operators to develop their technology as a pilot.

The following list provides a few other general concepts regarding the research stage of development:

- The research stage of development is a risk. It involves a large degree of funding and time, which in many cases can lead to abandoned technologies or concepts.
During the majority of the research stage, the effort is not closely tied to full-scale economics. Often, research teams are concerned with the fundamental working concepts. Normally, this causes the feasibility studies to concentrate on the potential beneficial sides of technologies.

The research stage creates an opportunity for all concepts, ideas and technologies to be considered.

There exists a diverse level of individuals involved at the research stage of development. Research groups can include independent researchers, university academics, consultants, governmental groups and industry.

There exists a variation of effort required to develop a technology, normally closely tied to the type of technology being developed.

### 7.3 Current Research in the Oil Sands

Current research in the oil sands industry can be divided into two broad categories; research for new technologies (and revisits of existing technologies) and research for technology enhancements. The following section will provide an overview of the current technologies being researched based on these two categories:

#### 7.3.1 New Technologies

Research for new technologies and revisits of existing technologies are investigations of unique implementations which act as stand-alone technologies. These technologies are normally revisits of current methods or original concepts for technological development.

Based on the investigation for current technologies being researched in the oil sands, there are 27 unique technologies being researched, with 15 being developed by proprietary vendors. Table 7-1 outlines the list of unique technologies currently being researched in oil sands. These are also summarized in Figure 7-1.

These technologies are ranked to show the quality of information available to the CTMC. An outline of the technology ranking system is provided below:

- **High**: The information on the sheet is referenced from published papers and peer reviewed documents. It contains graphics and has a sufficient amount of information to understand the processes associated with each technology.

- **Medium**: The information on the sheet contains some peer-reviewed data and provides a brief description of the technology.

- **Low**: The information on the sheet contains little to no data, has a very limited description of the technology and has made claims that are not supported by any peer review.
<table>
<thead>
<tr>
<th>#</th>
<th>Category</th>
<th>Technology group</th>
<th>Technology name</th>
<th>Ranking of sheet (high, medium, low)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-009</td>
<td>2. Extraction and Bitumen Recovery</td>
<td>i. Water Based</td>
<td>Bitumen extraction using CaO &amp; O3 or CaO and BD Apex Engineering</td>
<td>H</td>
</tr>
<tr>
<td>T-095</td>
<td>2. Extraction and Bitumen Recovery</td>
<td>i. Water Based</td>
<td>Electro-magnetic enhanced extraction (Tailings Elimination Technology, TET Technology) Chemviro</td>
<td>L</td>
</tr>
<tr>
<td>T-007</td>
<td>2. Extraction and Bitumen Recovery</td>
<td>iv. Other</td>
<td>RTR / Gulf extraction process</td>
<td>L</td>
</tr>
<tr>
<td>T-016</td>
<td>2. Extraction and Bitumen Recovery</td>
<td>iv. Other</td>
<td>CO₂ supercritical fluid extraction</td>
<td>M</td>
</tr>
<tr>
<td>T-358</td>
<td>2. Extraction and Bitumen Recovery</td>
<td>iv. Other</td>
<td>Mechanical processing of oil sands CryoEx Oil Ltd.</td>
<td>L</td>
</tr>
<tr>
<td>T-215</td>
<td>2. Extraction and Bitumen Recovery</td>
<td>iv. Other</td>
<td>Bitumen recovery using in-organic geopolymers Kemira</td>
<td>L</td>
</tr>
<tr>
<td>T-360</td>
<td>2. Extraction and Bitumen Recovery</td>
<td>iv. Other</td>
<td>Bitumen recovery using Osead hydrocarbons technologies OHT</td>
<td>L</td>
</tr>
<tr>
<td>T-185</td>
<td>3. Tailings Processing</td>
<td>i. Combined Tailings</td>
<td>NST production from the blend of cyclone underflow, thickener underflow and MFT using CaO or CaO &amp; CO₂ Apex Engineering</td>
<td>H</td>
</tr>
<tr>
<td>T-267</td>
<td>3. Tailings Processing</td>
<td>ii. Thickening</td>
<td>Froth treatment tailings thickening</td>
<td>M</td>
</tr>
<tr>
<td>T-205</td>
<td>3. Tailings Processing</td>
<td>ii. Thickening</td>
<td>Staged coagulation / flocculation Sethi Research and Testing Ltd.</td>
<td>M</td>
</tr>
<tr>
<td>T-054</td>
<td>3. Tailings Processing</td>
<td>ii. Thickening</td>
<td>Continuous mixing unit for flocculation (Tailings reduction through high shear) MetaFLO</td>
<td>L</td>
</tr>
<tr>
<td>T-067</td>
<td>3. Tailings Processing</td>
<td>iv. Filtration</td>
<td>Cross flow tailings filtration OSTRF</td>
<td>H</td>
</tr>
<tr>
<td>T-193</td>
<td>3. Tailings Processing</td>
<td>iv. Filtration</td>
<td>Electrokinetic dewatering - filter belt</td>
<td>H</td>
</tr>
<tr>
<td>T-085</td>
<td>3. Tailings Processing</td>
<td>vii. Other</td>
<td>Thermal drying (includes MFT brickmaking and other artificial drying technologies)</td>
<td>H</td>
</tr>
<tr>
<td>#</td>
<td>Category</td>
<td>Technology group</td>
<td>Technology name</td>
<td>Ranking of sheet (high, medium, low)</td>
</tr>
<tr>
<td>-------</td>
<td>------------------------</td>
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<td>--------------------------------------------------------------------------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>T-262</td>
<td>3. Tailings Processing</td>
<td>vii. Other</td>
<td>MFT treatment using inert micro-beads Omni Sync</td>
<td>M</td>
</tr>
<tr>
<td>T-222</td>
<td>4. Deposition</td>
<td>ii. Placement Methods</td>
<td>Sub-stratum injection of fine tailings Deltares</td>
<td>L</td>
</tr>
<tr>
<td>T-039</td>
<td>4. Deposition</td>
<td>iv. In-situ</td>
<td>Accelerated evapotranspiration using vegetation</td>
<td>H</td>
</tr>
<tr>
<td>T-056</td>
<td>4. Deposition</td>
<td>iv. In-situ</td>
<td>In-situ treatment of MFT (chemical and biological)</td>
<td>M</td>
</tr>
<tr>
<td>T-088</td>
<td>4. Deposition</td>
<td>iv. In-situ</td>
<td>Shock densification of soft tailings (blast, vibration, moving screens, bubblers)</td>
<td>M</td>
</tr>
<tr>
<td>T-209</td>
<td>4. Deposition</td>
<td>iv. In-situ</td>
<td>Electro-kinetic dewatering of fines</td>
<td>H</td>
</tr>
<tr>
<td>T-409</td>
<td>4. Deposition</td>
<td>iv. In-situ</td>
<td>Mini gulp skimming barge Water Planet Engineering LCC</td>
<td>L</td>
</tr>
<tr>
<td>T-550</td>
<td>4. Deposition</td>
<td>v. Capping</td>
<td>Tailings surface sealants to improve trafficability and limit infiltration</td>
<td>L</td>
</tr>
<tr>
<td>T-544</td>
<td>5. Water Treatment</td>
<td>iii. Physical &amp; Chemical Processes</td>
<td>Magnetohydrodynamics</td>
<td>L</td>
</tr>
<tr>
<td>T-549</td>
<td>5. Water Treatment</td>
<td>iv. Disinfection</td>
<td>Disinfection</td>
<td>L</td>
</tr>
<tr>
<td>T-435</td>
<td>6. Reclamation</td>
<td></td>
<td>Bioremediation of oil sands tailings using BioChar Carbon Basis Company Ltd.</td>
<td>L</td>
</tr>
</tbody>
</table>

*H, M, L = High, medium and low.*
Currently, the largest amount of oil sands research is being conducted to improve tailings processing techniques. Through the work of the FFTC, a large amount of information regarding the colloidal properties of tailings in water was documented. Other research is directed towards new bitumen and extraction methods, particularly solvent based extraction methods. Most of these technologies involve changes to current operations and in general, require a large degree of reviewed information to make informed decisions regarding their effectiveness at full scale. Technologies related to improvements of the current water based extraction technologies show the most promise.

Similarly, a large degree of research is being conducted on in-situ treatment of MFT. Historically, in situ treatment of mature fine tailings have been poorly understood, and there is now a focus in the research community to investigate treatment through technological advancement. Many of these technologies represent unique concepts not currently used in practice and have the capacity to assist our understanding of MFT and tailings dewatering. The majority of technologies in deposition are in their preliminary stages and it will be difficult to make informed judgement decisions regarding their capacity.

There is a lot of research devoted to refining reclamation technologies, with a focus on instrumented watersheds, development of end pit lakes, and water quality.

There is also considerable research and small pilots on water treatment technologies.
7.3.2 Technology Enhancements Research

Much of the research underway relates to improvements of the operational efficiency of existing systems (technology enhancements) rather than new technology. More specifically, most of the technology enhancements of interest are related to chemical amendments with the realization that such amendments can improve the operational efficiency of current technologies, and diversify their capacity for tailings management.

The majority of chemical amendments being developed are for use in tailings thickening processes, (in-situ, in-line or thickening). These chemicals demonstrate a variety of unique methods for the agglomeration of fines and in many cases, provide alternative beneficial applications for tailings management (i.e. efficiency of bitumen extraction, production of a non-segregating material, increased dewatering by development of floc structures).

An investigation of these third-party chemical amendments should be conducted to develop a more comprehensive understanding of the potential between technology suites.

7.4 Moving forward with research

There are numerous technologies and technology enhancements in the research stage that will be useful to consider either for additional research or development.

Technologies with an adequate amount of information (i.e. “High” in Table 7-1) should be evaluated for piloting as part of a development program. These technologies may be of interest by themselves, combined with other technologies, or to fill in gaps in the present commercial suites. There are several technologies for which there is not enough information for proper evaluation (“Medium” and “Low” designations in Table 7-1). A strategy for gathering further data for some of these technologies should form part of the roadmap.
8. OTHER OBSERVATIONS

This section provides a list of observations and lessons learned during the course of putting together this report.

- While no technology survey can be complete, a very wide net was cast to capture as many unique technologies as possible that may be important in meeting today’s oil sands tailings goals.
- It must be remembered that there is no one technology that can be applied to all oil sands mines, as each has unique geological and historical features. “There is no silver bullet”. There is a portfolio of commercially available technologies, of which suites of five to ten technologies can be employed in a commercial setting.
- Societal expectations for tailings continue to evolve, and the oil sands industry and regulators are evolving to meet these expectations. There is a strong desire on all fronts to expedite change.
- **The Technological Sieve:** Technologies working through fairly distinct stages of research, development, and commercialization is a bottom-up approach to adoption of new technologies. There are inherent difficulties in scaling research and development technologies, and even technologies employed at other mines. Oil sands tailings in many ways are unique (winter operations confound some technologies) and the scale of the operation and the tailings flux rates are one to three orders of magnitude larger than many other mines. It takes a decade or longer to bring new technologies to their full potential.
- The Roadmap provides a snapshot in time. The OSTC needs to develop a mechanism to continue to scan for new technologies, and support research and development.
- There is room for better integration of tailings technologies where used in sequences. In particular, variability of input streams into tailings processes has created significant restrictions for new technologies. Methods to reduce this uncertainty either at the source, or more likely, through pre-processing, will be required.
- The science of polymers continues to evolve quickly, and new polymers provide new tailings processing options. The environmental impacts of polymers and their degradation products needs to be fully understood before their widespread use.
- Historically, there has been too much technical optimism around each new tailings technology, and as a result new technologies are oversold and sometimes prematurely implemented. There has also been too much planning optimism, with little robustness built into short and long-range tailings plans. A more conservative approach to technology development, technology design, and planning is indicated. There must be a recognition that this takes time. Where optimistic goals are not met, there are typically both environmental and economic penalties to be paid.
• Fundamentally, most tailings technologies come down to either concentrating fines in their own stream or storing them in the porosity of the sand tailings. And among the fine tailings disposal schemes, either the process is saturated or unsaturated.

• One of the major opportunities for improvement is greater management / governance of the entire tailings selection / construction / planning / operating system, with a greater focus on creating tailings landscapes with acceptable environmental and land use performance at a reasonable cost. The same rigour that is routinely applied to safety, geotechnical stability, and production of bitumen and synthetic crude oil, needs to be brought to tailings.

• There is a major opportunity for industry to test and adopt standard protocols for geotechnical and geo-environmental testing of oil sands tailings.

• There is an opportunity to develop a standard list of screening tests for new technologies and publish the results of all tests in a publically available database.
9. CONCLUSION AND RECOMMENDATIONS

This section brings together the conclusions and recommendations interspersed within the report. Some of the activities are work that would build on learnings from this report, others are enhancements or additional activities based on the findings from the Component 1 work.

9.1 Recommendations for future work

The following recommendations pertain to work building on the findings of this report:

- Carry out a gap analysis of the commercial processing and deposition suites to evaluate the potential for continuous improvement of existing technologies and addition of new complementary technologies. Options for better management of commercial tailings streams should be reviewed and a strategy for achievement should be developed.

- Review the list of development stage technologies contained in this report that merit advancement towards commercialization.

- Review the list of technologies that are commercial elsewhere, as identified in this report that merit advancement towards commercialization.

- Investigate third-party chemical amendments to develop a more comprehensive understanding of the potential interchangeability between technology suites.

- Evaluate the list of research technologies. Technologies with an adequate amount of information have been identified in this report and should be evaluated for piloting as part of a development program. These technologies may be of interest by themselves, with other technology, or to fill in gaps in the present commercial suites. There are several technologies collated for which there is not enough information for proper evaluation. A strategy for gathering further data for some of these technologies should form part of the roadmap.

- Revisit the plan for evaluation of reclamation and water treatment technologies in view of the new information regarding their mature state of commercialization and the applicability of existing methods and their variations to a wide range of oil sands tailings conditions.

9.2 Recommendations for Continuous Improvement And Technology Development

There is an opportunity that the classification framework presented herein be considered for further use. A formal scanning framework should be developed for examining new technologies as they are identified, to augment the database and funding of further research into new technologies.
Each site will have its own unique characteristics that will favour different technology suites. Approximate ranges of possible conditions for these factors and some conceptual implications for tailings management are discussed in more detail in Appendix C. **There is an opportunity for each mine operator to evaluate the technology suites hand in hand with each mine plan developed for each lease.**

There are a large number of technologies in the research stage, most of which are being advanced by third-party vendors. The quality of the available data is highly variable and would benefit for some standardized tests. **There is an opportunity for the industry to provide a mechanism for soliciting and evaluating third-party oil sands tailings technologies.**

Some of the remaining technologies relate to management systems and monitoring. There is an opportunity for further development of monitoring techniques (slurry flow metres, slurry fines content metres, density metres, field sampling techniques, remote sensing, etc.) that are not covered in this report. **There is an opportunity as part of continuous improvement and enhanced governance/management of oil sands tailings. The OSTC should develop more reliable and robust methods for slurry and depositional monitoring.**

### 9.3 State of Practice Recommendations and Conclusions

- **Mining and Extraction Technologies:** The large scale mining equipment used in the oil sands mining industry does not readily permit selective mining except where there are large contiguous blocks of low grade ore (waste islands). **There is an opportunity to reduce the fines that are sent to the crusher. This should be considered during the mine planning stages.**

  Water based bitumen extraction methods are mature technologies and are key to current oil sands economics. They are unlikely to be replaced without significant development of new methods, with proven economics and commensurate (step change) benefits to tailings, with the potential exception of retort based extraction, but only if environmental and economic factors can be addressed.

  There are outstanding concerns regarding the carryover solvents, pyrite and metals, and naturally occurring radioactive minerals (NORMS) in the froth treatment tailings. It is unclear whether these materials form discrete deposits or are diluted along with the extraction tailings after deposition. **There is an opportunity for the existing froth tailings deposits to be characterized. Process methods to reduce or manage these loadings should be investigated on a priority basis.**

- **Tailings Processing and Deposition Technologies:** There is a major opportunity to increase the performance and decrease the cost of existing commercial tailings technologies and suites employed at the oil sands operations. Component 1 has identified eight commercial technology suites. Almost all of the suites rely upon slurry discharge methods, tailings consolidation, water recycle, and mechanical capping for reclamation. Current regulations are focussed on the shear strength of the soft tailings only, whereas trafficable surfaces require compatibility between the cap and the underlying soft tailings.
Current plans and regulations for stabilization, capping, and reclamation of soft tailings deposits should be re-examined for compatibility with material properties (both capping materials and underlying tailings), the scale of the operation, costs, and the desired landscape performance. Various methods for hydraulic capping should be included in this evaluation.

9.4 Summary of Technology Suites

A high level overview of current practice for each of the eight technology suites provides the following recommendations:

**Conventional Hydraulic Fill Construction:** There is opportunity through more engineering and operational efforts to further increase the fines capture rate during conventional hydraulic fill construction, thus reducing the MFT production rate. This opportunity for “managed beaching” should be investigated through fundamental work and large trials.

**Water Capped MFT:** Water Capped MFT is a technology which accepts that the MFT will consolidate over a very long time period, in the range of hundreds of years. Syncrude and other operators await the assessment of a full-scale demonstration of this technology at “Base Mine Lake”, as in-pit, water capped sequestration of MFT. This concept is a planned component of closure plans for all mines now in operation. End pit lake performance, the rate of bio-degradation of naphthenic acids in the process water cap, the potential for permanent or semi-permanent stratification, re-suspension and mixing of lake bottom sediments and the rate of release water from the underlying MFT at large scale are the predominant remaining technical matters to be verified. There is an opportunity to look at densifying MFT prior to placement in end pit lakes.

**Composite Tailings:** There is opportunity to examine the engineering properties of lower SFR Composite Tailings (nominal 3:1) that would reduce the reliance on sand for composite tailings production, increase the fines capture, and provide better non-segregating behaviour. Producing higher density CT discharge would increase the fines capture and make a more robust operating system. More consideration should be given to lower SFR CT operationally, improve methods of CT discharge, and high density CT.

**Thickened Tailings:** There is opportunity for continuous improvement of all aspects of producing thickened tailings, to reduce costs and increase reliability. Component 1 recommends a systematic review of industry wide oil sands thickener operating and deposit performance, with a view towards improved reliability, and optimizing the SFR and density of the discharge, to maximize consolidation behaviour required cappable deposition. This will probably require a departure from high rate thickening towards thickener technologies that can readily produce and handle a denser underflow product.
In-line Thickening with Thin Lift Dewatering: There are major opportunities to improve technologies including process, deposition, management, and cost. The oil sands industry should conduct a thorough review of the performance of the field studies conducted at Suncor, MRM, and Syncrude. The review should include a common basis, consistent definitions, a field database of performance, and a common understanding on the underlying physics of actual and potential evaporation.

In-line Thickening with Accelerated Dewatering: In-line thickening with accelerated dewatering may have niche applications for beneficiating MFT. Ongoing monitoring of the Syncrude pilot should be undertaken with a view to developing an understanding of the role of cracking and rim ditching on the densification behaviour.

Centrifuging MFT: Centrifuging MFT has potential for broad application to MFT beneficiation, similar to that of thin lift drying. Testing to date at the Syncrude site indicates that a reliable cake is achievable at high production rate with the commercially available centrifuges. Studies are underway to evaluate conveyor stacker operations. Feasibility level evaluations should be undertaken to optimize the material handling schemes based on results from the pilots to date.

Coke Capping: The opportunity to evaluate wick drain performance in soft tailings is one of the main benefits of coke capping for the industry. The Suncor wick drain pilot should be monitored to determine the potential of wick drains to dewater fluid fine tailings. The efficacy of wick drains fluid fine tailings dewatering should be resolved.

9.5 Reclamation and Water Treatment

There are mature reclamation technologies available to treat trafficable surfaces and prototype efforts for water capping of fluid tailings (end pit lake technology) are ongoing. While not the focus of this study, there remain research and development opportunities to improve the performance and develop new reclamation techniques. This work is already being carried out by industry, regulators, academics and through multiparty groups like the Cumulative Effects Management Association (CEMA).

There are a wide variety of mature water treatment technologies available within the oil sands and from non-oil sands industries worldwide. In general, the development of water treatment applications for the oil sands industry is not specific to any one tailings technology. Technologies can be adapted to oil sands process water relatively rapidly as needed. A roadmap for development of water treatment technologies is largely beyond the scope of the present project. If there were discharge water quality guidelines for the oil sands, there would be an early opportunity to develop passive and active water treatment technologies for discharging process affected water back to the environment. This would reduce engineered containment requirement for tailings ponds and allow for more aggressive progressive reclamation.
10. REFERENCES


CEMA, 2010. “Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region.”


