Review of Reclamation Options for Oil Sands Tailings Substrates

BGC Engineering Inc.

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Oil Sands Research and Information Network

Oil Sands Research and Information Network

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

OSRIN provides:

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

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

Citation

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REPORT SUMMARY

BGC Engineering Inc. (BGC) conducted a scoping study of the state of knowledge related to technologies for reclaiming oil sands tailings substrates to upland boreal forests and wetlands for the Oil Sands Research and Information Network (OSRIN). The objective of the scoping study is to help establish an understanding of the status of fine tailings reclamation technology in the Athabasca Oil Sands Region (AOSR). Relevant research was compiled from peer reviewed and non-peer reviewed sources including journals, conference proceedings, magazine articles, internal and consultant reports. Industry researchers and academics were contacted for their information.

Until recently, a wet landscape scenario, in which mature fine tailings (MFT) would be stored in pits and capped with a layer of freshwater to form an artificial lake, was the most likely reclamation option for MFT. In this scenario, pit lakes (PL), or end-pit lakes (EPL) are designed to remediate process-affected waters from tailings landforms through bioremediation and dilution. As an alternative to water-capping, much of the current research has focused on reclamation technologies that would result in a dry landscape.

Reclamation of fine tailings using a dry landscape scenario first requires stabilization of the deposit to allow access for heavy machinery (trafficability). Soil cover designs and revegetation prescriptions are used to reclaim the tailings substrate to an equivalent land capability or ecosystem function. Wetland design and upland forest reclamation are active areas of research in fine tailings reclamation, including the potential impacts of increased salinity on plant species selection, germination and growth.

CAVEAT

ACKNOWLEDGEMENTS

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1 INTRODUCTION

BGC Engineering Inc. (BGC) was requested by the Oil Sands Research and Information Network (OSRIN) to describe the state of knowledge related to technologies for reclaiming oil sands tailings substrates to upland boreal forests and wetlands based on the available literature. The objective of the scoping study is to help establish an understanding of the status of fine tailings reclamation technology in the Athabasca Oil Sands Region (AOSR).

The aim of this report is to serve as a planning document for future research initiatives by OSRIN and other research agencies to support, promote and improve the oil sands industry's capability to deal with the challenges of reclaiming their fine tailings. A companion report produced by BGC for OSRIN summarizes emergent fine tailings technologies in the region (BGC 2010).

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

1.1 Background

The AOSR is located in the boreal forests of Northern Alberta and contains one of the largest deposits of oil in the world with an estimated bitumen volume of 1.7 trillion barrels (Fung and Macyk 2000). The oil sands are overlaid by glacial deposits and saline sodic Cretaceous shale known as Clearwater Formation (overburden). This report focuses on mineable oil sands in which surface mining techniques in large open pits are used to remove the overburden material to recover the underlying ore body. The extraction process requires large amounts of hot water (0.6 to 0.7 m^3/ tonne of oil sand) and caustic (sodium hydroxide) to separate the bitumen from the sand (Hadwin et al. 2006). The main waste product of this process is tailings slurry, which contains solids, process water and unrecovered bitumen (MacKinnon and Sethi 1993). Fine tailings, along with overburden and coarse tailings sands, are the major types of mine wastes that require reclamation in the oil sands region (Fung and Macyk 2000) using either wet or dry landscape technologies (Quagraine et al. 2005).

Tailings are hydraulically transported and stored in large tailings ponds. Upon deposition, the coarse sand particles rapidly segregate from the slurry and settle at the edge of the tailings ponds, leaving the fluid fine tailings to accumulate in the center of the pond. Fines consist of silt and clay particles, bitumen and water. It is a common practice for the surface mined oil sands industry to define fines as mineral particles smaller than 44 µm. Fine tailings (FT) has an initial solids content of around 8%, and settles over a period of time (~2 years) to form mature fine tailings (MFT) at a solids content of 30% to 35%. MFT requires decades to centuries to densify and turn from a fluid to a semi-solid material, resulting in the need for long term storage requirements before MFT reaches a shear strength adequate enough to support reclamation materials (FTFC 1995).
BGC (2010) provides further description of the extraction process and MFT properties.

The accumulation of large volumes of fluid tailings on the post-mined landscape is a major environmental challenge in the oil sands region (FTFC 1995). Until recently, a wet landscape scenario, in which MFT would be stored in pits and capped with a layer of freshwater to form an artificial lake, was the most likely reclamation option for MFT. In this scenario, pit lakes (PL), or end-pit lakes (EPL) are designed to remediate process-affected waters from the tailings landforms through bioremediation and dilution. As an alternative to water-capping, much of the research has focused on reclamation technologies that would result in a dry landscape.

Upland reclamation to a dry landscape is not achievable until the surface deposit consolidates or solidifies and is trafficable for operational equipment. Composite or consolidated tailings (CT) is an example of a commercially operational technology that results in a dry landscape when sand capped. CT is created by mixing tailings sand, MFT and gypsum to form a non-segregating tailings stream that can be geotechnically stable (~80% solids) in less than one year (Mikula et al. 1998). Many tailings technologies aim to increase the solids content of the fine tailings – physical/mechanical methods (filtration, centrifuge), natural processes (evaporation, freeze/thaw, evapotranspiration), chemical (flocculants) and biological, as discussed in BGC (2010).

Historically, reclamation research has focused on the establishment of upland forest vegetation and the use of soil materials (peat and overburden) to improve plant growth performance on mine wastes (tailings sand and overburden). More recently, government is also requiring operators to salvage and use upland surface soils (LFH layers) in place of peat or peat:mineral mixes. Techniques developed for upland reclamation are potentially transferable directly to fine tailings reclamation. As a result, BGC conducted a review of available references related to oil sands upland and wetland reclamation technologies that can be applied to fine tailings reclamation, and indicated at a high level, areas of active research and potential research gaps.

1.2 Need for the Study

Reclamation of tailings sand dykes and overburden dumps has been ongoing since 1971 at Suncor and 1976 at Syncrude (Anderson et al. 1998). This study was commissioned because oil sands operators are starting to reclaim different substrates arising from a variety of tailings management options (BGC 2010). These substrates are more challenging to reclaim than tailings sand dykes and overburden because they:

- Have higher moisture content
- Have higher salinity
- May need more capping material placed between the substrate and the surface soils
- May require specialized techniques for reclamation soil placement
- May be subject to differential subsidence
- Require different topographic design to control water release

1.3 Scope of Work

As part of this study, an assessment of potential research gaps was conducted based on an analysis of existing literature. The specific objectives of the scoping study are to:

1. Identify and synthesize relevant peer reviewed and publically available non-peer reviewed literature related to reclamation of fine tailings, and
2. Identify gaps in the current state of knowledge.

1.4 Review Approach

Relevant research was compiled from peer reviewed and non-peer reviewed sources including journals, conference proceedings, magazine articles, internal and consultant reports. Library and government databases were searched for available references. Key university researchers, industry personnel and consultants were identified and sent introductory letters requesting their information. Reclamation researchers provided peer reviewed publications and graduate theses. Several reclamation manuals developed by multiparty groups in the oil sands, especially those through the Cumulative Environmental Management Association (CEMA) were used for initial synthesis.

Currently there are four producing oil sands operators in the region: Suncor Energy Inc. (Suncor), Syncrude Canada Ltd. (Syncrude), Shell Canada Ltd. (Shell), and Canadian Natural Resources Limited (CNRL). Several more mines are under development or in various stages of proposal and/or regulatory approval. Industry personnel from these operators were also contacted for information. A large amount of work has been undertaken by various research organizations and oil sands mine operators to develop techniques for effectively reclaiming fine tailings. However, much of this work has yet to be made public. As a result, relevant research may be missing from this report as only documents obtained through public sources were used. Appendix 2 provides a list of references reviewed as part of the scoping study – only the key references used to compile the report are cited in the References section.

2 TAILINGS AND LAND RECLAMATION OVERVIEW

2.1 Reclamation Process

Returning oil sand tailings deposits to productive ecosystems similar to those existing prior to disturbance is a significant challenge in the oil sands region. The reclamation process includes several steps: reclamation material salvage, hauling and placement, landform grading, fertilizer application, revegetation, monitoring and certification (Syncrude 2006). Figure 1 displays a general reclamation process from reclamation material salvage to certification. Progressive reclamation is practiced in the region to reclaim areas as soon as possible after mining, waste disposal or plant decommissioning. The ultimate goal of the reclamation process is to certify the land and return it back to the Crown.

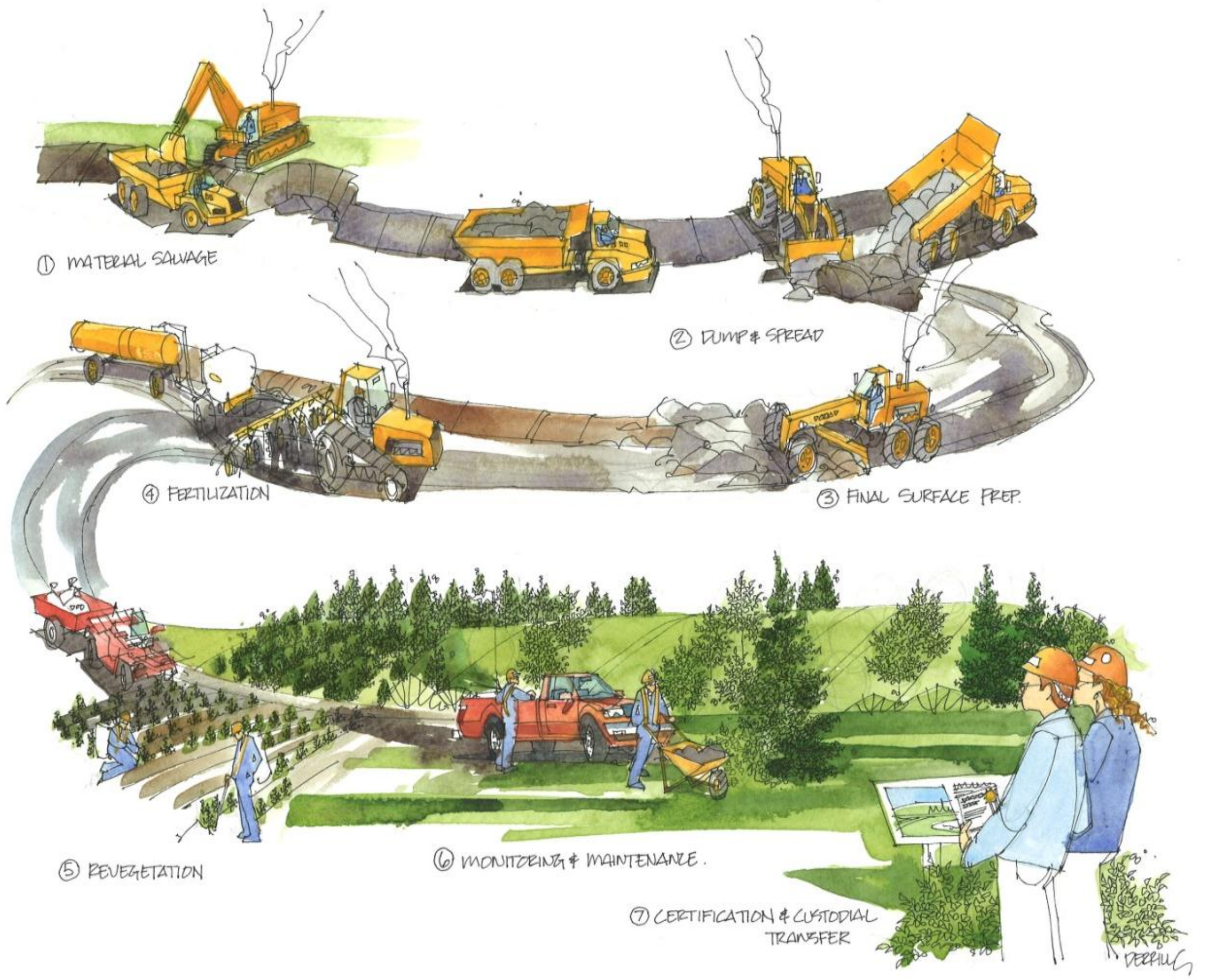

Figure 1. Typical Reclamation Process

Table 1 provides a general description of each stage of the reclamation process.

Table 1. Summary of Reclamation Activities

Reclamation Activity	**Description**[1]	**Timing**
Reclamation Material Salvage	• Organic soils (peat, muskeg, LFH layers) to the underlying mineral layer are salvaged from areas prior to surface mining • Material either direct placed or put in stockpile for future use	• Generally done 2 years in advance of mining

Reclamation Activity	Description[1]	Timing
Hauling and Placement	• Material hauled and placed as per reclamation soil prescriptions • Material is placed in either one-lift (cover soil only), or two-lifts (cover soil and suitable subsoil) • Direct placement is preferred method to retain seedbank and other vegetative propagules	• Typically occurs in the winter months to ensure trafficability of organic soils and to minimize compaction of cover soils
Landform Grading	• Contouring the land and adding natural appearance elements (e.g., microtopography)	• Generally the summer following placement
Fertilizer Application	• Typically fertilizers are applied to enhance nutrient availability at a standard application rate	• Follows landform grading/ contouring activities
Seeding	• Barley (*Hordeum vulgare*) is sown to provide vegetation cover and erosion control • Pasture areas are seeded with grass/legumes by harrowing	• Seeded prior to reforestation
Revegetation	• Native woody tree species are planted at an average density of 2,000 stems/ha; shrubs at a density of 500 stems/ha for commercial forestry • Planting prescription designed to achieve a target ecosite	• Trees usually planted in the spring or fall within 2 to 3 years of material placement
Monitoring	• Vegetation monitoring on-going and includes free-to-grow surveys	• Vegetation monitored at regular intervals
Certification	• Decommissioning and custodial transfer to the Crown	• Following an appropriate a period of monitoring agreed upon with regulators

1: Activity descriptions modified from Syncrude (2006)

2.2 Operating Approvals

The following sections provide a brief summary of the regulatory context for fluid tailings reclamation. Alberta Environment (AENV) and Alberta Sustainable Resource Development (ASRD) regulate oil sands development and manage the environment, including conservation and reclamation planning. The Energy Resources Conservation Board (ERCB) regulates oil sands mining and process operations, including tailings management. Operators are required to assess and report on their annual reclamation activities and submit updated closure and reclamation plans to regulators.

2.2.1 *EPEA*

Mining companies are required to reclaim disturbed areas as set out within the *Environmental Protection and Enhancement Act* (EPEA; Government of Alberta 2000). Regulations require industry to achieve "land capability equivalent" to that which existed prior to disturbance (although the end land use may be different), such as establishing commercial forests within the range of natural ecosites found in the Central Mixedwood Sub-Region of the Boreal Forest (Beckingham and Archibald 1996). Recent emphasis has also been placed on understanding and maintaining "ecosystem function" of forested and wetland landscapes (Reclamation Criteria Advisory Group 2008).

The goal of reclamation is to return disturbed areas to diverse, self-sustaining boreal forest ecosystems, capable of supporting a variety of end land uses (e.g., Syncrude 2007). Predisturbance land use capabilities include timber harvesting, wildlife habitat, watershed functions, wetlands, sources of traditional foods and medicinal plants, and recreation (CEMA 2009, OSVRC 1998).

Prior to mining, the region consisted of upland deciduous forests and wetland complexes (Naeth and Wilkinson 2004). The upland areas are primarily composed of deciduous forests with the dominant tree species being trembling aspen (*Populus tremuloides*), white spruce (*Picea glauca*) and balsam poplar (*Populus balsamifera*). On drier, sandier sites communities of jack pine (*Pinus banksiana*) dominate. Within lowlands, the dominant tree species are black spruce (*Picea mariana*), white birch (*Betula papyrifera*) and tamarack (*Larix laricina*). Currently, reclamation activities focus on establishing upland forests with a portion of wetland areas.

2.2.2 *ERCB Directive 074*

A recent directive from the Energy Resources Conservation Board (ERCB) establishes new requirements for tailings operations in the oil sands. ERCB Directive 074 sets out specific performance criteria for the reduction of fluid tailings and the formation of trafficable deposits (ERCB 2009a). Several long term objectives for tailings management are outlined with the overall goal to minimize and eventually eliminate long-term storage of fluid tailings in the reclamation landscape, and create a trafficable surface as early as possible to facilitate progressive reclamation.

Reclamation of fine tailings deposits to a desired dry landscape is not possible until the surface is trafficable and able to support heavy equipment. Bearing capacity and ultimately trafficability are governed by the density and undrained shear strength of the deposit. Fine tailings have strengths that usually lie somewhere between a fluid and a solid. Figure 2 (adapted from McKenna 2009) shows the shear strength continuum for soft tailings.

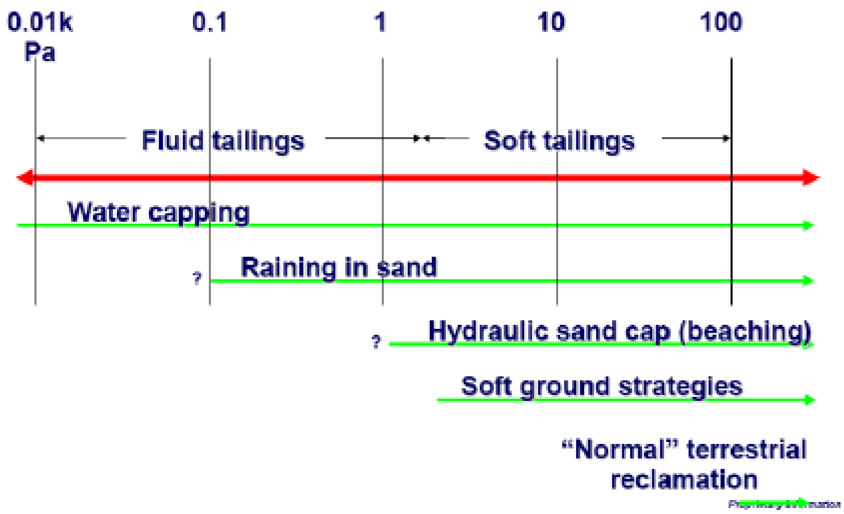

Figure 2. Soft Tailings Shear Strength Continuum.

ERBC Directive 074 (ERBC 2009a) provides performance objectives for tailings management based on the shear strength of the deposit. The minimum undrained shear strength of 5 kPa must be attained for the material deposited in the previous year, and the deposit must be ready for reclamation within five years after active deposition has ceased. The deposit will have the strength, stability, and structure necessary to establish a trafficable surface. The trafficable surface layer must have a minimum undrained shear strength of 10 kPa. Directive 074 also requires that oil sands operators deposit a significant portion of their annual production of fine tails in Designated Disposal Areas (DDA), which must be formed in a manner that ensures trafficable deposits. Emergent tailings technologies must achieve these shear strength targets within a reasonable time period, as essentially the type of reclamation technology employed for a tailings deposit will depend primarily on the strength of the material.

As noted in Figure 2, direct trafficking of soft tailings beaches requires specialized equipment – most operators plan to cap their soft tailings with hydraulically placed tailings sand which allows for use of medium sized mining equipment for reclamation. Sand capped tailings can be reclaimed to a mix of upland forests and wetlands.

2.2.3 *Regional Guidelines*

Regional manuals such as the *Land Capability Classification System for Forest Ecosystem* (LCCS) are intended to facilitate evaluation of equivalent land capability for upland forested ecosystems in natural and reclaimed lands in the AOSR (CEMA 2007a).

This manual is used in conjunction with the *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region* developed by the Oil Sands Vegetation Reclamation Committee (OSVRC)(CEMA 2009, OSVRC 1998) to prescribe revegetation plans for reclaimed landscapes based on the target ecosite (Beckingham and Archibald 1996).

Historically the majority of reclamation research has focused on the establishment of upland forest vegetation, and the use of soil materials (peat, LFH layers and overburden) to improve plant growth performance on a dry landscape. However, recent emphasis has been placed on the reclamation of wetlands in the oil sands region.

Wetlands cover approximately half of the undisturbed, natural landscape in the boreal forest, and include bogs, fens, marshes, shallow open water wetlands and swamps. The *Guideline for Wetland Establishment on Reclaimed Oil Sands Leases* provides a context for wetland reclamation in the region (CEMA 2007b). In the absence of regional case studies, existing wetland guidelines in the oil sands region rely heavily on observations from natural analogues and opportunistic wetlands on oil sands leases (CEMA 2007b). Wetland reclamation is being performed operationally in the region, and several field scale trials are underway to advance fen and bog reclamation on fine tailings and improve regional guidelines. EPL reclamation is presently in the development stage with at least one large scale trial underway.

2.3 Climate

A short growing season, cool temperatures and greater evaporation compared to precipitation are challenges to revegetation in the oil sands region (Naeth and Wilkinson 2004). Long term mean annual temperature is 0.7 ^{o}C, with January being the coldest month (-18.8 ^{o}C) and July the warmest (16.8 ^{o}C) as recorded from the Environment Canada monitoring station located at the Fort McMurray Airport (56^{o} 39'N, 111^{o} 13'W) as summarized in Table 2. Long-term mean annual precipitation is 455 mm. Annual lake evaporation is 578 mm, resulting in an annual water deficit.

Table 2. Summary of Long-term Climate Averages at Fort McMurray

Month	**Temperature (^{o}C)**			**Total Precipitation (mm)**	**Relative Humidity (%)**	**ET* (mm)**
	Minimum	**Mean**	**Maximum**			
January	-24.0	-18.8	-13.6	19.3	74.4	-3.3
February	-19.8	-13.7	-7.6	15.0	75.2	-0.8
March	-13.2	-6.5	0.3	16.1	75.7	16.6
April	-3.3	3.4	10.0	21.7	74.1	59.4
May	3.3	10.4	17.4	36.9	72.9	102.1
June	7.9	14.7	21.4	74.8	78.5	121.6
July	10.2	16.8	23.2	81.3	84.1	129.2
August	8.6	15.3	21.9	72.7	87.9	101.9
September	3.3	9.4	15.4	46.8	87.3	52.6
October	-2.2	2.8	7.8	29.6	82.7	19.2
November	-12.8	-8.5	-4.2	22.2	81.0	-2.0
December	-21.4	-16.5	-11.6	19.3	76.1	-4.5
Average	**-5.3**	**0.7**	**6.7**	**455.5**	**79.2**	**591.4**

* Evapotranspiration (ET) modeled using HSPF model

3 RECLAMATION TREATMENT TECHNOLOGIES

Returning oil sands tailings deposits to productive ecosystems similar to those that existed prior to disturbance is a significant challenge in the oil sands region.

In a wet landscape tailings reclamation scenario, the only reclamation option is to store MFT in pits capped with a layer of freshwater to form an artificial lake[1]. Current research has focused on reclamation technologies that would result in a dry landscape as an alternative to this scenario. Reclaiming fine tailings to a dry landscape requires stabilization of the deposit for trafficability, the addition of soil cover, watershed and topography reconstruction and finally revegetation. As a result, the reclamation treatment technologies were divided into the key technologies used to create wet and dry landscapes including:

- Wet Landscape Scenarios
- Dry Landscape Scenarios
  - Trafficability and Stabilization
  - Soil Cover
  - Watershed Reconstruction and Topography
  - Salinity Controls
  - Revegetation
- End Land Uses

The following information is provided for each technology:

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

[1] Wet landscapes may be created in other parts of the mine such as overburden dumps and aggregate resource sites. This report does not address those reclamation schemes.

Brief descriptions of these stages (modified from Flint 2005 and shown in Figure 3) are presented below.

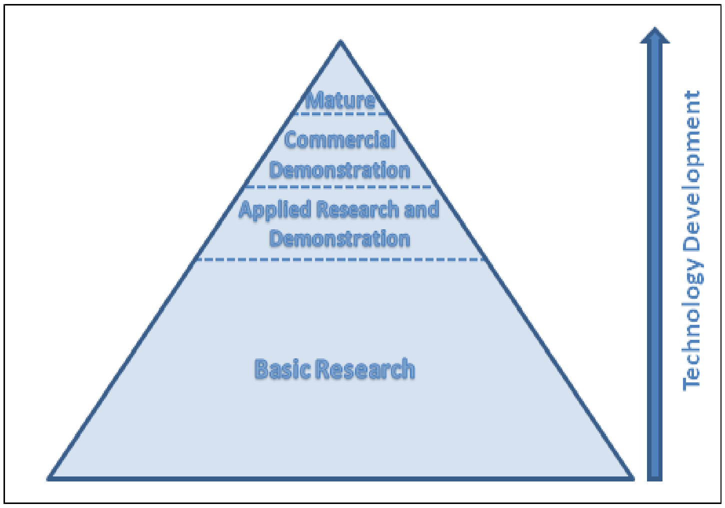

Figure 3. Stages of Technology Development.

Basic research is often performed in universities, as well as government labs and industry research labs. The intent of the work does not necessarily have any defined commercial intent, but is designed to extend the frontiers of knowledge. Basic research provides improved understanding of the processes and development issues towards the more commercial stage of development. Basic research is characterized by experimentation and frequent failure or dead ends. Effort or costs are relatively modest in the early stages. Some refer to this stage as developing "pre-competitive" or "enabling" technologies.

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

Commercial demonstrations occur when technologies move from basic research status towards the potential for commercial application, and individual industry players will move to development to meet commercialization timeframes. This work is devoted to development, often with large prototype operations or pilots. At this stage, technology development can be much more costly. Due to the expense involved in piloting a technology, intellectual property can be patented and/or kept confidential. Demonstrations are often funded by the end user of the technology.

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

It should be noted that basic research program may cost a hundreds of thousands of dollars, pilots several million dollars, and commercial implementation hundreds of millions of dollars. Accordingly, only a few technologies reach the pilot stage, and fewer to the commercial stage. These are often considerable difficulties in scaling technologies that worked well at the basic research stage to the commercial or mature stage.

3.1 Wet Reclamation Scenarios

3.1.1 *MFT Water Capped Lake*

In a wet landscape scenario, MFT is stored in a mined out pit and capped with a minimum of a 5 m layer of water to form an artificial lake. The use of this technology eliminates the need for operational equipment to reclaim the MFT other than pumps and pipelines to move the MFT from the tailings pond to the pit and oil skimmers to collect any oil found at the discharge point. Over time, the MFT will consolidate, slowly releasing pore-water into the base of the water cap and adding to the thickness of the water cap.

This technology is still in the demonstration stage, with Syncrude's Base Mine Lake (BML) being the region's first full commercial scale demonstration MFT water capped lake. In this scenario, pit lakes (PL) or end pit lakes (EPL) are designed to remediate process-affected waters from the tailings landforms through bioremediation and dilution. Research has examined the potential for MFT to mix with the overlying water cap due to surface wave action and stratification of turnover processes, and the optimum water cap thickness to prevent turnover (Boerger et al. 1990, 1992, Gulley and MacKinnon 1993, MacKinnon and Boerger 1991, MacKinnon et al. 1995).

Methane evolution and biodegradation of bitumen hydrocarbons are also cited as potential problems for the remediation of fine tailings using a wet reclamation scenario. The consumption of methane by aerobic bacteria is hypothesized to contribute to anoxic conditions in the water cap, resulting in depleted oxygen levels which could prevent establishment of a functioning lake ecosystem (Quagraine et al. 2005).

Process water and MFT contain high levels of naphthenic acids (NAs), which are acutely toxic to many aquatic organisms. Some studies have shown natural degradation in water capped lakes can result in a significant reduction in toxicity, along with microbial activity as determined using laboratory cultures (Quagraine et al. 2005). However, it is unclear whether microbes are capable of adapting and completely biodegrading naphthenic acids.

Quagraine et al. (2005) report that although NAs have been documented to biodegrade naturally over time, there appears to be a portion of NAs (referred to as refractory NAs) that degrade over significantly longer time periods. CEMA (2007b) indicates that a hydraulic retention time of several months is required for degradation of labile NAs (toxic fraction) in wetlands and lakes, and several years for refractory NAs.

During mine life, process-affect water is maintained onsite in large settling ponds and recycled because of the "zero discharge" policy until water quality criteria are obtained. Flint (2005) identified future areas of research to include treatment of the intermediate layer between the MFT and the top recycled later in tailings ponds.

Specific objectives identified including additional research to contribute to:

- Faster release of water from fine tailings for recycle.
- Faster release of interstitial water in sand deposits for recycling.

- Treatment for the water layer between MFT and the surface water layer for recycling and reuse.
- Treatment of settling pond water for discharge to receiving water bodies such as the Athabasca River.

Refer to the Section 3.3.3 for further discussion of PL/EPL and an assessment of the knowledge gaps associated with this technology.

3.2 Dry Reclamation Scenarios

3.2.1 *Trafficability and Stabilization*

As an alternative to water capping, research has focused on reclamation technologies that would result in a dry landscape. Stabilization of the tailings deposit is essential prior to the application of reclamation soil materials and revegetation as a dry landscape.

Appendix 3 provides a summary of stabilization and capping techniques for each of the tailings technologies identified in BGC (2010). Because many of these technologies are in the initial stages of development, or basic research, strategies for stabilization may not be reported. Assessment of tailings stabilization techniques that are commercially operational are provided in the following sections including hydraulic and mechanical capping.

3.2.1.1 Hydraulic Sand Capping

Hydraulic sand capping involves discharging tailings sand to create beach-above-water deposits that are between 2 m to greater than 5 m thick to act as a sand cap. This technology is actively employed in the oil sands for sand capping CT and MFT. Hydraulic sand capping offers the most cost effective and efficient solution for stabilizing soft tailings, but requires large volumes of tailings sand and initial tailings planning. With this technology, large hummocks are required for water table control. A 2 m distance between the top of the reclamation cover to the water table in the tailings sand is required to minimize water logging and salinization of the rooting zone.

The CT prototype on Syncrude's Mildred Lake Settling Basin (MLSB) is an example of a CT deposit hydraulically capped with 5 m of tailings sand during winter conditions with 1 m of frost using 100 tonne trucks.

Pros

- Established technology.
- Relatively simple and cost-effective technology (3 to 4 times less expensive than other technologies).
- Techniques for applying soils and revegetation are developed.
- Uses standard operational equipment.

Cons

- Underlying deposit must have undrained shear strength of at least 5 kPa and similar density to the tailings sand cap to allow access for small equipment.

- Requires large volumes of tailings sand material and water for transport.
- Reduces the amount of tailings sand available for CT production.
- Requires water table controls (e.g., hummocks) for hydraulically placed sand and coke.
- Liquefaction of material possible even after consolidation.

Knowledge Gaps

- Optimization of sand cap thickness to prevent salinization of rooting zone, provide for adequate flushing of salts and allow trafficability; while also considering the availability of tailings sand as an operational concern.

State of Technology

- Mature (operates commercially).

3.2.1.2 Hydraulic Coke Capping

Hydraulic coke capping is also a technology used in the oil sands, including commercial operations. Syncrude estimates that approximately 20% of the closure landscape will consist of coke-based landforms (Syncrude 2006). Currently, Syncrude's MLSB contains a coke cap which overrides fluid MFT at a 20 m to 30 m depth. Standard reclamation techniques are expected to be used to reclaim the coke cap once the material is stable and trafficable. A 1 m cover is required to provide sufficient moisture. Preliminary investigations into the leachability and combustibility of coke indicated that the coke has minimal leaching and combustibility potential when capped with reclamation material (Syncrude 2006). Field scale reclamation studies were commenced in 2003 as part of a five-year research plan between Syncrude, Suncor and CNRL to address coke reclamation issues such as coke capping of soft tailings and hydraulic reclamation.

Pros

- Established technology.
- Relatively simple and cost-effective technology.
- Techniques for applying reclamation soil materials and revegetation are developed.
- Uses standard operational equipment.

Cons

- Requires water table controls (e.g., hummocks) for hydraulically placed coke.
- Trafficability issues.
- Coke is considered a natural resource and must be stored and accessible for future use (ERCB 2009b).

Knowledge gaps

- Incorporation of other waste streams (e.g., sulphur, coke, gypsum).
- Floating coke covers over a geosynthetic clay liner (GCL) over soft tailings requires further research.

State of Technology

- Mature (operates commercially).

3.2.1.3 Mechanical Tailings Sand Placement

Mechanical tailings sand placement involves placing thin lifts of tailings sand material over geogrid to improve trafficability. This technique is referred to as the "fairies and teaspoon" approach because it requires small equipment placing material often one bucket at a time. Soft tailings deposits have been capped using this method, such as Syncrude's U-Shaped Cell, a pilot CT demonstration on MLSB.

Pros

- Established technology, widely used.
- Techniques for applying reclamation soil materials and revegetation are developed.
- Uses standard operational equipment.
- Frost can improve results.

Cons

- Expensive due to equipment time.
- Underlying deposit must have a sufficient bearing capacity and similar density to the tailings sand cap to allow access for small equipment.
- Surface not trafficable to large reclamation equipment.
- Requires large volumes of tailings sand material.
- Reduces the amount of tailings sand available for CT production.

Knowledge Gaps

- Techniques to improve the formation of a crust (e.g., freeze/thaw) to improve trafficability and cost-effectiveness of technology.

State of Technology

- Mature (operates commercially).

3.2.2 *Soil Cover*

Soil cover designs are used to enhance the physical, chemical and biological properties of tailings once the deposit is trafficable to machinery. Mineral soil, peat and LFH from the originally stripped area as well as from undisturbed sites are mixed and used to cover mine substrates prior to revegetation (CEMA 2009, OSVRC 1998).

Several soil amendments have been researched for capping fine tailings including overburden, tailings waste and sewage waste, however these amendments are not as effective as peat and overburden (Naeth and Wilkinson 2004). The following sections assess reclamation soil materials and soil amendments used to reclaim these substrates. The assessment was limited to those technologies have shown promise for use in fine tailings reclamation.

3.2.2.1 Peat and Overburden

The properties of tailings sand make it a poor substrate for plant growth including low water storage capacity, low organic material, poor nutrient status, high erosion potential, high sodium content, hydrophobic properties, low cation exchange capacity and the absence of microbial activity (Fung and Macyk 2000). Crusting at the surface of the deposit can inhibit water infiltration. CT has similar limitations, and due to low porosity is also limited by waterlogging (Li and Fung 1998). As a result, reclamation soil materials are required to provide a favorable growing medium for plants. Table 3 provides a summary of the typical physical properties of end substrates including overburden, tailings sand, CT, coke and fine tailings.

Table 3. Summary of Typical Substrate Properties.

Substrates*	**Electrical Conductivity (dS/m)**	**Sodium Adsorption Ratio (SAR)**	**pH**	**Texture (%)**	**Hydraulic Conductivity Range (m/s)**
Tailings Sand	3	50	8 to 9	5% Clay 80% Sand 15% Silt	10^{-6} to10^{-5}
Clearwater Overburden	4 to 12	17 to 37	7 to 8	46% Clay 8% Sand 46% Silt	10^{-10} to 10^{-5}
Tailings Sand Seepage Water	1 to 3	3 – 10	6.2 to 6.7	N/A	N/A
Composite Tailings	2 to 7	>40	7 to 9	9% Clay 78% Sand 13% Silt	10^{-9} to $2x10^{-6}$
Coke	If slurried, similar to tailings sand	If slurried, similar to tailings sand		Syncrude coke is fine sand; Suncor coke is sandy gravel	10^{-6} to 10^{-2}
Mature Fine Tailings (MFT)	Similar properties as tailings sand			8% Clay 57% Sand 35% Silt	10^{-9} to 10^{-6}

* Properties from Qualizza (2000), McKenna (2002)

Direct revegetation of tailings sand and CT has been attempted previously in the region. Germination and emergence rates were low and plant growth was stunted due to a lack of nutrients (Naeth and Wilkinson 2004). Research indicates that a combination of tailings sand, peat and overburden materials is the best soil material to improve plant emergence and establishment (Naeth and Wilkinson 2004) by improving soil structure, moisture retention and nutrient availability in tailings sand (Takyi et al. 1977). Increasing depths of peat:mineral mix over tailings sand significantly increased total soil moisture (TSM) to 90 cm (Moskal 1999). Changing the ratio of peat to mineral mix from 1:1 to 3:1 also increased TSM, but not significantly.

Reclamation soils are placed in layers (or lifts) on mine waste substrates at depths specified in the Alberta Environment operating approvals. Seven main prescriptions have been used within the region including peat:mineral mix, subsoils, tailings sands, overburden, Clearwater shale or lean oil sands (Rowland et al. 2009), although different materials and capping depths are adopted depending on conditions.

Pros

- Proven technology to enhance plant growth on tailings sand (historic area of research).
- Cost-effective and uses standard reclamation equipment.
- Plant germination and emergence rates high.

Cons

- Requires reclamation planning to assure a positive material balance.
- Stockpiling and material re-handling can destroy native seed and propagules.
- Stockpiles often a source for aggressive non-native species.
- Recent regulatory changes are driving increased use of LFH.

Knowledge Gaps

- Hydraulic placement of reclamation material.
- Optimal cover thickness for wetland establishment and decomposition of peat under saturated conditions.
- Understanding long-term soil moisture and nutrient dynamics in soft tailings caps.
- Understanding and predicting salt movement from tailings into reclamation materials.
- Additional research required on the optimal placement depth of peat material for wetland development.

State of Technology

- Mature (operates commercially).

3.2.2.2 LFH

LFH is a thin organic layer on the forest floor consisting of litter (L), fibric (F) and humic (H) material and contains many viable seeds and propagules. The addition of LFH material has showed promise as a source of plant propagules, organic matter and soil micro fauna on reclaimed substrates (MacKenzie 2006) and is now a requirement in regulatory approvals. Research has been conducted as both greenhouse and field trials (MacKenzie 2006), and is currently a commercial operational technology in the oil sands. Two application depths (10 cm and 20 cm) have been tested and applied to cover soil designs in the oil sands region.

Pros

- LFH shown to enhance plant community diversity, species richness, plant abundance and soil nutrient availability as compared to peat soils.

Cons

- Benefits of LFH source reduced by stockpiling.
- Not enough LFH materials available for all surfaces requiring reclamation (low quantity of material available).
- Uncertainty in terms of best uses for limited LFH resources.

Knowledge Gaps

- Use of LFH for creating upland boreal forests on tailings sand hummocks.
  - For example, upland forest research challenged to create A/B ecosites; potential use of LFH to create A/B ecosites on a commercial scale.
- Investigation into which species (shrubs, herbs) are recruited from LFH applications conducted at a commercial scale for upland and wetland revegetation.
- Uncertainty around the long-term vegetation community benefits of LFH vs. traditional peat:mineral mixes.

State of Technology

- Mature (operates commercially).

3.2.3 *Watershed Reconstruction and Topography*

3.2.3.1 Watershed Design

Watershed topography is critical for establishing a closure surface water drainage system with creeks, wetlands and lakes. Without drainage or topographic controls, large areas would become affected with excess salinity, resulting in sterilization of reclamation soils and mortality of vegetation. Watershed reconstruction and topography controls are linked. Contouring, relief structures and meso-topography are essential for promoting positive water drainage and trafficability on tailings sand deposits.

A drainage system for a tailings storage facility could include a dendritic pattern of drainage channels on the top of the facility collecting to an armoured main outlet channel, a series of collector ditches at the toe of the landform to collect seepage and wetlands to attenuate flows. Several guidelines exist in the region to design water courses using a geomorphic approach (Golder 2004, 2008). Tailings pouring needs to be conducted in a way that supports positive closure drainage; for example, by pouring from the entire perimeter of the pond.

Landform design that considers upland and wetland topographic ratios and configurations is also identified as important for managing surface and groundwater interactions and long-term landscape sustainability (Flint 2005).

Pros

- Landform design for overburden dumps is well established.

Cons

- Perception that watershed reconstruction and topographic controls requires significant operational resources.

Knowledge Gaps

- Watershed reconstruction to control water balance and fluxes of process-affected water.
- Determining optimum topographic configurations and ratios (uplands, wetlands) to manage surface and groundwater interactions.
- Developing methods to reduce tailings sand containment footprint.
- Landform design techniques for establishing self-sustaining, self-repairing drainage system for natural appearance and landform integration with creeks, wetlands and lakes.

State of Technology

- Mature (operates commercially).

3.2.3.2 Topographic Controls

Hummock and swale topography is designed for the majority of tailings sand storage area plateaus for seepage and water table control. Meso-topography in the form of large sand hummocks is a developing technology in the region. Various methods for upland hummock construction have been considered and tested, including constructing sand ridges built by spiggotting at select locations or through mechanical placement. Hummocks need to be included in the engineering design and should be high and wide enough to provide adequate water table control. Hummocks designed for Syncrude's Sandhill Fen range in height from 3 m to 8 m in height and approximately 400 m in length with a variety of side slopes. Modeling has shown hummock flushing in relatively short time frames (approximately 20 years) and substantial decreases in salinity (BGC 2008).

Topographic controls are critical to maintain a water table a minimum of 2 m below the ground surface to minimize the potential for salt accumulation in the upper soil layers. Controls include meso-topography in the form of raised sand hummocks or swales. Price (2005) conducted a hydrogeology study on the South West Sand Storage Facility at Syncrude and found that the water table was within 1 m of the surface on 93% of the study area with EC ranging from 2 dS/m to 3 dS/m.

Pros

- Topographic controls are achievable using standard operational equipment.
- Effective water table control method.
- Placement of hummocks enhances natural appearance and provides terrain for upland forest reclamation.
- Produces diversity of topographic positions, soil moisture and salinity conditions.

Cons

- Flushing rates depend on the hydraulic conductivity of tailings material, with coarser tailings (e.g., cycloned) expected to flush more rapidly than normal tailings sand.

Knowledge Gaps

- Further empirical data and modeling required for long-term flushing rates from hummocks constructed using different tailings materials and configurations.
- Research into the optimal hummock design (shape, slope, aspect, orientation, height) for flushing salts and preventing salinization of the rooting zone.
- Planting schemes for hummocks (uplands, wetlands and transition zone between zones).
- Implications of hummock design on end land use options (drainage channels, commercial forestry, wildlife habitat).
- Flushing rates as a function of hummock height.
- Understanding hydrological processes at transition zones between upland hummocks and wetlands.

State of Technology

- Commercial demonstrations.

3.2.3.3 Designing for Differential Settlement

Watershed and topographic designs for fine tailings can be affected by differential settlement, especially when high water content materials are used as construction materials. High water content materials that consolidate can release a significant amount of water resulting in large land subsidence and alteration of the initial topographic design with time.

Consolidation is a process in which water is released from the soil under applied stress, resulting in settlement and a denser material. Rates of consolidation decrease exponentially over time (Figure 4). The rate of consolidation depends on material properties, applied stress and drainage conditions and if external conditions are similar, typically clay materials will exhibit slower consolidation but larger settlement compared to sandy materials. An example of differential settlement is when whole tailings are deposited into a tailings pond; sandy material will segregate on the dyke and beach while fine tailings with large amounts of water travel to the middle of the pond. This situation creates two areas with materials that have different consolidation behaviours (fine tailings in the middle of the pond will have larger settlement and require longer time to complete consolidation). Under saturated conditions, a metre of settlement typically results in a metre of release water, which can potentially salinize the reclamation cap.

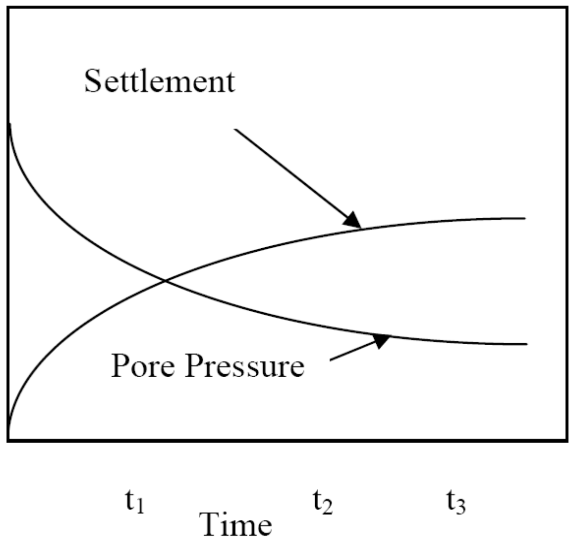

Figure 4. Settlement and Pore Pressure Dissipation in Sand Capped CT

If the tailings being reclaimed result from several tailings technologies, and are placed in the same area, deposits with varying materials types and therefore varying amounts of settlement can be expected – however this spatial variability in settlement has not been examined. CEMA's *Landscape Design Checklist* (RWG 2005) indicates that landform designs must take into account the long-term settlement of the materials to accommodate for settlement and control undesirable ponding.

Pros

- Easy to manage 0 m to 2 m of settlement with swale and hummocky topography resulting in "fen-like" and marshy areas.
- Post-reclamation settlement creates micro-topographic diversity.

Cons

- Difficult to manage > 2 m of post-reclamation settlement.
- Greater than 4 m of settlement may result in excessive ponding and or flooding at outlet elevations.
- Reclaimed areas may require on-going maintenance to manage settlement, potentially delaying reclamation certification.

Knowledge Gaps

- Post-reclamation settlement may play a role in increasing micro-topographic diversity in the post-reclamation landscape, although this mechanism is yet to be studied.
- Spatial variability in settlement as a result of applying multiple tailings technologies.
- Further development of models to predict areas of settlement.

State of Technology

- Mature (operates commercially).

3.2.4 *Salinity Controls*

3.2.4.1 Seepage

Seepage water from the tailings facilities is managed during operations with perimeter ditches, sumps, and seepage recovery wells. Collector drainage channels are required at the toe of the tailings sand storage areas to collect seepage. In addition, monitoring wells are in place to monitor any potential releases of process-affected water off site. Seepage water is expected to increase in salinity over time due to water recycling measures (Qualizza 2000), which could have severe implications for plant community development.

Long term strategies for managing seepage zones are required for closure, one of which is the creation of saline wetlands at the toes of tailings ponds and overburden dumps to bio-remediate saline process-affected seepage water. Naturally saline boreal wetlands, those with EC greater than 10 dS/m, may serve as natural analogues for reclamation of seepage zones (Purdy et al. 2005).

Pros

- Seepage controls are used industry-wide to capture and re-treat process-affected water.
- Opportunity to design wetlands at the location of seepage zones.

Cons

- Seepage water is expected to increase in salinity over time which will have an implication on the selected plant species.
- Potential need for more saline wetlands than is common in the boreal forest.

Knowledge Gaps

- Quality of leached water from various waste materials and reconstructed topography.
- Characterizing process-affected seepage waters from tailings sand, CT deposits and newer tailings management technology deposits (e.g., Suncor’s Tailings Reduction Operations – Suncor 2009).

- Quantifying the amount of process-affected water not recovered by seepage controls, including monitoring of groundwater flow systems.
- Research needed in the area of salinity controls to better quantify the long term water quality of seepage water discharged from newly reclaimed tailings landforms.
- Suitability and availability of native plant materials for use in saline wetlands.
- On a regional scale, a better understanding of the environmental impacts of process-affected seepage water discharge on receiving water bodies such as the Athabasca River.

State of Technology

- Mature (operates commercially).

3.2.4.2 Underdrains

The primary objective for the application of underdrains is for salinity control, but underdrains are also found to increase the trafficability of the tailings deposit. Field observations have shown that the use of underdrain technologies can enhance soft tailings strength and trafficability by increasing consolidation rates.

Underdrains have been used in the construction of Syncrude's Sandhill Fen Instrumented Watershed to control the upward flux of saline tailings water into the reclamation materials on a tailings deposit (BGC 2008). In this operation, underdrains were installed 2 m below the tailings surface using a plough train of dozers working on a nominal 30 cm frost cap, and consisted of a perforated pipe covered with a fine screen geotextile mesh. The Sandhill Fen is being constructed on a consolidated CT deposit with a 13 m sand cap.

Pros

- Salinity controls to reduce salinity of reclamation soils.
- Increased trafficability of a soft tailings deposit.

Cons

- High operational costs.
- Operationally challenging to install.

Knowledge Gaps

- Technical documentation of operational techniques used to install and monitor underdrains.
- Understanding the "zone of influence" of each underdrain for seepage control.
- Optimizing the number of underdrains per hectare to effectively control seepage on a deposit.

- Examining alternative materials as underdrains (such as gravel).

State of Technology

- Commercial demonstrations.

3.2.5 *Revegetation*

Vegetation establishment is essential for returning fine tailings deposits to productive ecosystems in a dry landscape. Salinity and moisture are the greatest limitation to germination and establishment on soft tailings (Naeth and Wilkinson 2004). Moisture deficits and excesses are both challenges to revegetation.

3.2.5.1 Plant Selection

Release water from the CT consolidation process is relatively high in salinity due to the presence of sodium, chloride and sulfate ions in addition to boron at concentrations that can be toxic to plants (MacKinnon et al. 2001). Previous studies have shown the response of woody plant species and tailings substrates and release waters varied depending on the species (Renault et al. 1998, 2001, 2003, 2004). Conifer species (white spruce, jack pine) showed significant growth reductions on a two year old CT deposit, while shrub species such as willow (*Salix* sp.) showed relatively high tolerance. Salt-tolerant grasses such as barley, slender wheatgrass (*Agropyron trachycaulum*) and altai wild rye (*Elymus angustus*) have also been shown to have potential for use in early reclamation of "soft" pre-consolidation CT (Renault et al. 2003, 2004). Slender wheatgrass and wild rye also showed relatively high tolerance when grown in reclamation soil irrigated with CT water, and in CT substrates amended with peat in greenhouse trials (Renault et al. 2004).

Salinity toxicity has major implications for vegetation establishment on soft tailings as many plant species, including wetland plants, show significant levels of sensitivity to elevated conductivity and sodium (CEMA 2007b). Salts accumulate in the reclaimed landscape from the ore deposit itself, recycling of the process-affected waters, and leaching of marine shale overburden deposits (Leung et al. 2003), and can occur at concentrations that cause plant mortality. Saline soils can be defined as having an electrical conductivity greater than 4 dS/m, an exchangeable sodium percentage less than 15% and a pH usually greater than 8.5 (Purdy et al. 2005).

Examples of sub-saline and saline marshes exist in the boreal forest at the range of salinities expected in the oil sands (Trites and Bayley 2009a, b), suggesting there is a potential to use salt-tolerant species in reclaimed wetlands. Purdy et al. (2005) explain that forest vegetation can potentially establish over saline soils, as long as the salts are below the rooting zone. However, the study also cautions that it may be unrealistic to expect plant communities in saline areas to proceed in similar trajectories as native boreal forest vegetation because many native species are not salt tolerant (Purdy et al. 2005).

Historically, revegetation research has focused on the establishment of upland forest vegetation including woody plant selection and the use of soil (peat and overburden) to improve plant growth performance on tailings sand. The majority of revegetation research conducted on tailings sand has focused on tree species, specifically jack pine, black spruce, white spruce and trembling aspen and the effects of the chemical, physical and hydrological properties of tailings sand on growth and survival (e.g., Burgers 2005).

Pros

- Techniques established for upland reclamation can transferable to soft tailings reclamation.

Cons

- Upland boreal species may be intolerant to saline and moisture conditions.
- Inadequate supply of native seed.
- Direct planting of mine wastes (tailings sand, saline/sodic overburden, CT) unsuccessful.
- Soil salvaging techniques reduce the viability of seed and plant propagule sources.

Knowledge Gaps

- Revegetation of overburden, tailings sand and consolidated tailings with a soil cap is well established, but less well known is the establishment of sustainable ecosystems with natural processes.
- Native shrub propagation and planting at a commercial scale.
- Salinity tolerances of wetland plants.
- Selection, availability and planting of wetland plants at a commercial scale.
- Role of mycorrhizal associations for plant suitability on CT.

State of Technology

- Mature (operates commercially).

3.2.5.2 Hydro-seeding

Hydraulic reclamation involves the piping of slurries containing soil amendments and seed sources onto fine tailings areas that are inaccessible by heavy equipment. Dispersal of seeds in a slurry form, or hydroseeding, is commonly used on mine sites to seed steep slopes or unstable substrates (Roberts and Bradshaw 1985). Slurries have been widely used to facilitate dispersal of soil amendments which enhance plant growth in agriculture and have been found to improve soil moisture and nutrient availability. Few studies investigating the potential for hydraulic reclamation of soil and vegetation were identified.

Pros

- Reduced seed losses and increased seedling establishment and cover.
- Reduced operational costs as compared to traditional soil placement using heavy equipment.

Cons

- High seeding rates are required to account for losses from wind.
- Seed and propagules float rather than settle into the soil.
- Higher operational costs as compared to traditional broadcast seeding.

Knowledge Gaps

- Identification of soil amended slurries that can flow through a pipe.
- Selection of plant species that can germinate in a given slurry.

State of Technology

- Basic Research (operational outside of oil sands region).

3.2.5.3 Fertilization

Typically fertilizers are applied to enhance nutrient availability at a standard application rate. Early strategies involved applying fertilizer directly to the soil followed by annual maintenance applications (OSVRC 1998). During the 1970's, application rates were based on agriculture production recommendations for forage crops, and periodic assessments of available soil nutrients in soils (Suncor). However annual maintenance applications were reduced to minimize the potential for plant competition between planted trees and herbaceous cover (OSVRC 1998).

Although there has been a general decreasing trend in the number of fertilizer applications for reclaimed sites, Rowland et al. (2009) suggest that reclamation treatments that are repeatedly fertilized are more likely to develop into a target ecosite.

Pros

- Fertilization can increase the cover and biomass of species planted for the first few years after establishment.

Cons

- High fertilizer application rates reduce soil microbial activity and mycorrhizae infection rates and may decrease performance of some native species and legumes.
- Fertilizers potentially add to the salt burden of the soil.
- Alberta Sustainable Resource Development is concerned about the sustainability of vegetation and communities following withdrawal of fertilizer applications.

Knowledge Gaps

- Further research required to optimize fertilizer application rates and methods to increase germination and long term growth of native species.
- Potential to "push" plant community towards a specific target ecosite using fertilizers, but this is poorly understood.

State of Technology

- Mature (operates commercially).

3.3 End Land Uses

A challenge of reclaimed landscapes is to ensure that they meet stakeholder expectations and performance objectives. End land uses can include commercial forestry, recreation, traditional use, natural areas and wildlife habitat. Because so many fine tailings reclamation technologies are under development, it may not be clear how the technology will meet end land use goals – or in the case of saline tailings areas, whether the abiotic and biotic processes will develop in a similar trajectory to native ecosystems.

3.3.1 *Wetlands*

Wetlands are an important component of the boreal forest landscape. Peat-forming wetland classes, specifically bogs and fens (perched fens) cover 43% of the pre-disturbance landscape compared to marshes (2%), shallow open water wetlands (1%) and swamps (<1%). It is currently thought that wetlands will be constructed on a large proportion of soft tailing deposits in areas connected to shallow surface drainage (CEMA 2007b). However, a strong understanding of the structure and function of reclaimed wetland systems, as compared to native wetlands remains under investigated (Cooper 2004).

Fen wetland design and construction is a major area of research in the oil sands region (BGC 2008). Marshes and ponds have been constructed on the reclaimed landscape; however there is currently only one fen wetland in construction on Syncrude's East In-Pit (BGC 2008). Syncrude's Sandhill Fen Instrumented Wetland (~15 hectares) is the first fen to be established at the commercial scale and is the largest attempted on a soft tailings deposit. It is also the first time that the entire watershed has been specifically designed to support a sustainable wetland. Research findings, including soft tailings reclamation techniques, will be used to update the wetland design guide for the region (CEMA 2007b).

Successful fen wetland restoration has been documented in areas where peat mining has destroyed or altered the wetland (Amon et al. 2005, Cooper and MacDonald 2000, Richert et al. 2000), but occur at spatial scales much smaller (<0.5 hectares) than scales anticipated for the oil sands region. Rochefort (2000) defined successful restoration of peatlands as the re-establishment of a native plant cover consisting of Sphagna or brown mosses, and the development of functioning acrotelm and catotelm layers, essentially living peat (aerobic) above decomposing peat (anaerobic).

Re-establishing the site-wide hydrology is a critical component of the wetland design. Hydrology influences chemical and physical processes in the wetland such as salinity, nutrients and oxygen levels, acidity, sediments, and hydroperiod. Wetlands need a constant water supply to sustain wetland plants and maintain saturated soils. Water inputs include precipitation, surface runoff, groundwater or process-affected water discharge. Because wetlands in the region will need to be sustained in water deficit conditions (precipitation < evapotranspiration), understanding the hydrology of constructed wetlands is critical to their sustainability. In fen wetlands, the water table is relatively stable, at or slightly above the soil surface, while the hydrology of bogs is driven by precipitation inputs.

A major challenge to wetland reclamation will be excessive salts entering the reclaimed landscape from mine or tailings substrates. Studies have been initiated to attempt to quantify the response of wetland plant species to salinity gradients (e.g., Syncrude U-Shaped Cell study), as well as to characterize the native vegetation communities in sub-saline and saline marshes in the region. Trites and Bayley (2009b) surveyed 25 natural boreal wetlands along a salinity gradient and found an EC range of 0.5 dS/cm to 28 dS/cm (similar or higher than those expected for oil sands reclamation). Operational controls such as under drains and freshwater inputs are important design elements for Syncrude's Sandhill Fen to attempt to manage salt inputs until wetland plants are established.

Stockpiled and salvaged live peat materials are the recommended topsoil for wetland reclamation with peat material placed at least 0.5 m to 1.0 m deep, tapering shallower on upland slopes to allow for natural peat accumulation (CEMA 2007b). A thicker peat layer is thought to help establish a vertical structure for the development of the acrotelm-catotelm layers. A current CEMA project is examining the ability of saline-tolerant sedge and reed species to accumulate organic matter and produce peat (CEMA 2007b), while a Syncrude funded project is also examining the response of wetland species to different soil placement depths, treatments and hydrological conditions including process-affected water (BGC 2008). Transplanting of whole acrotelm layers has also shown promise in peatland revegetation (CEMA 2010).

Successful re-establishment of dominant fen species has been demonstrated in fens altered by peat mining using treatments such as sowing seeds and transplanting seedlings, rhizomes and cuttings from natural fen donor sites (Cooper and MacDonald 2000). Salvaging and importing substrate and plant propagules from a nearby donor wetland is also an established reclamation method (Mitsch and Gosselink 2007). Donor material (seeds, rhizomes, and moss and plant propagules) collected from the top 10 cm in natural fens and placed by hand on disturbed fens, significantly increased plant cover/richness (Cobbaert et al. 2004). An initial application of straw mulch (3,000 kg/ha) improved the abundance of fen plants, but did not significantly increase plant cover after year one. Phosphate fertilizer application (2 g/m^2) prior to revegetation has been proposed to enhance establishment of vascular plants (Cobbaert et al. 2004).

Pros

- Discharge areas located in low spots on tailings plateaus in sand capped soft tailings, or at the toes of tailings dam slopes on original ground, are possible locations for fen wetlands.

Cons

- Freshwater inputs are required to control salinity while vegetation is established.
- Fen wetlands may require user inputs (fertilizers, freshwater, underdrain controls) for several years.

Knowledge Gaps

- Documented case histories from the region with detailed empirical data on fundamentals for wetland design including:
  - percolation rates for upland areas.
  - actual evapotranspiration rates.
  - climate histories (as input to models).
  - substrate saturated and unsaturated permeabilities and soil-water characteristic curves.
  - vegetation planting schemes.
  - designs for inflow and outflow structures for oil sands areas.
  - typical reclamation equipment and unit costs.
  - topographic controls (wetland:upland ratio, watershed area).
- Strategies for growing and planting salt tolerant vegetation at an operational level.
- Better understanding of how wetlands will transition from moderate to low salinity over decades and centuries as soft tailings consolidate.
- Geosynthetic clay liners (GCLs) have been used in wetland design, but are not required for design. The longevity of GCLs for perched wetlands is a design issue. Additional research is required to protect deterioration from freeze-thaw and chemistry effects for permanent reclamation.
- Operational techniques for salvaging and transplanting live peat.
- Techniques for returning peat-accumulating plant species and the impacts of salt on establishment on a site.
- Uncertainty whether vegetation in the oil sands region can be effective in removing a significant portion of salts from solution by plant uptake.
- Hydrological (and hydrogeological) processes that will sustain wetlands over time.
- Potential of wetlands as carbon sinks; understanding the carbon balance.
- Changes in microbial community structure over time.
- Potential indicators of reclamation success and time frame for monitoring.
- Refer to a recent scoping study conducted by CEMA (2010) for additional knowledge gaps, including interviews with key academic wetland researchers.

State of Technology

- Commercial demonstrations.

3.3.2 *Upland Forests*

Reclamation of tailings sand dykes and overburden dumps has been ongoing since 1971 at Suncor and 1976 at Syncrude (Anderson et al. 1998). Early reclamation focused on erosion control by seeding areas with grasses and legumes. A shift in focus from erosion control to "self-sustaining ecosystems equivalent to pre-disturbance conditions" required a significant change in reclamation techniques. Currently, revegetation plans are developed with consideration for the target ecosites identified for the boreal mixedwood forests based on extensive study. A total of twelve ecosites have been identified for the Central Mixedwood Subregion (Beckingham and Archibald 1996).

Upland plant communities develop in response to local soil moisture and nutrient conditions, which are linked to substrate and topographic position in the boreal forest (Bridge and Johnson 2000). Figure 5 (adapted from Beckingham and Archibald 1996) provides a conceptual model for ecosite development on a hillslope based on the vegetation and environmental gradients determined by Beckingham and Archibald (1996).

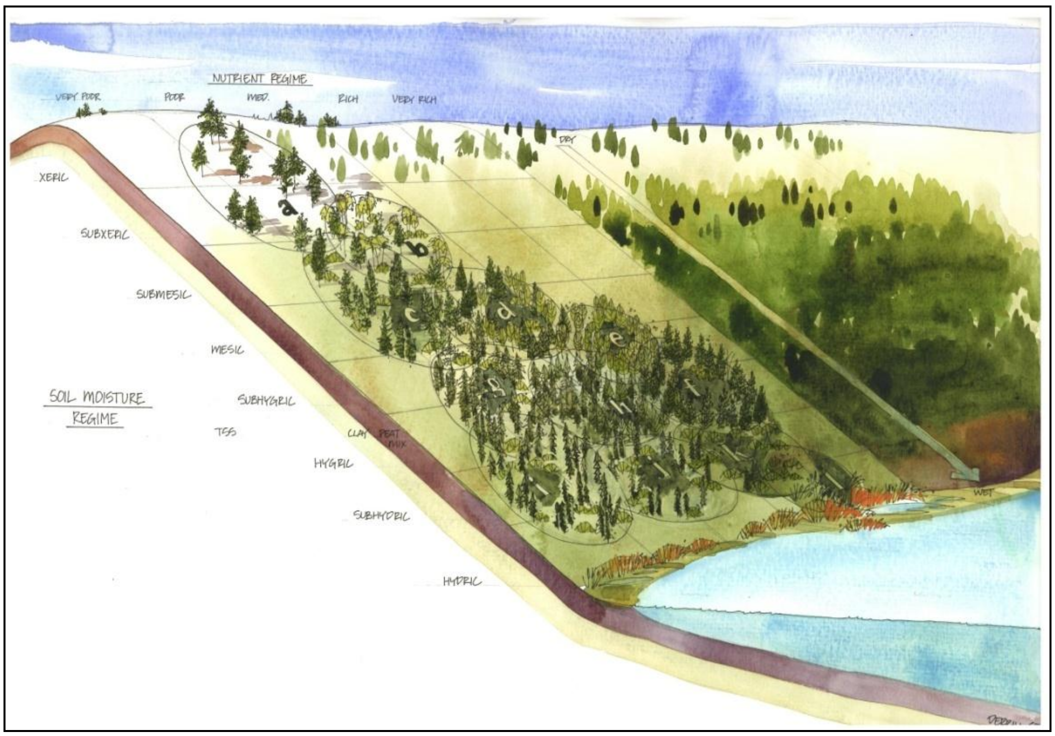

Figure 5. Conceptual Model of Target Ecosites in the Central Mixedwood Subregion.

Planting prescriptions are designed using the tree species best suited for the particular reclamation site including soil moisture and nutrient regimes and topographic position, and are designed using a species composition that accelerates the process of natural succession towards desired target ecosites (OSRVC 1998). Because plant communities are understood to develop along certain successional pathways (e.g., to a climax white spruce-aspen stand for upland forests), OSRVC (1998) recommends planting species representative of different successional stages to ensure that as succession proceeds the later successional species will be available for colonization.

Although successional pathways are conceptually understood, the critical recovery process for ecosystems is not well understood (Flint 2005). Additional research is required to predict ecosystem processes and plant community dynamics in the future, and to also model community responses to climate change scenarios. Johnson and Miyanishi (2008) argue there is a fundamental difference in the approaches of the physical process studies (e.g., hydrology and geomorphology) and the vegetation and wildlife studies in the oil sands, in that the former often takes a physically based approach to model processes and validate their understanding to make future predictions. This suggests that revegetation research should attempt to understand the processes that give rise to observed vegetation and successional patterns.

Pros

- Extensive body of research and regional guidelines available for upland forest revegetation.

Cons

- Saline tailings areas may not project towards the ecosites characteristic of native boreal forests.

Knowledge Gaps

- Revegetation of soil caps on mine wastes (overburden, tailings sand, CT) are understood – less understood is target ecosite and reconstruction and establishment of boreal forest ecosites.
- Maximum rooting zone depths for individual plant species.
- Continued emphasis on understanding mycorrhizal development to enhance plant establishment.
- Recovery processes for ecosystems from disturbances (e.g., fire, drought, erosion, beaver activity, etc.) is not well understood.
- Process-oriented physically-based models for vegetation community development over time.
- Modelling required to understand the potential impacts of climate change on vegetation, hydrology and soil moisture using a range of greenhouse gas emission scenarios.

State of Technology

- Mature (operates commercially).

3.3.3 *Pit Lake*

Pit Lakes (PL), or End Pit Lakes (EPL), are engineered waterbodies established in excavated areas or mined out pits, usually at the lowest topographic position or elevation of the mine site. Due to their location on the landscape, PL/EPL are often central features in the landscape, and their outlet elevation controls much of the mine topography to ensure positive inflows and proper outflows. PL/EPL function as bioreactors and mixing areas for passive treatment of process-affected water from tailings landforms through bioremediation and dilution, prior to discharge to receiving water bodies.

The purpose of PL/EPL is to be productive and sustainable landscape features at closure, including functioning littoral zones. Toxicity from naphthenic acids is mitigated by ensuring an adequate retention time in the lake, while salinity effects are potentially diluted by freshwater inputs. The reclaimed landscape is designed to maximize the flow from reclaimed areas to the PL/EPL, including sources of runoff and groundwater seepage.

PL/EPL are designed with two distinct layers, including a bottom substrate consisting of overburden or reject material and a freshwater cap; some PL/EPL may also have a middle layer consisting of a soft tailings deposit such as MFT or Thickened Tailings (TT). Clearwater Consultants (2007) provides an updated EPL design guide for the region.

Syncrude's Base Mine Lake (BML) contains MFT at a thickness of 50 m and will be capped with 5 m of water starting in 2012 in fulfillment of the Syncrude 1993 commitment to implement this fine tailings capping technology at the commercial scale (Syncrude 2006). MFT transfer to BML started in 1995, shorelines were reclaimed in 2007 and connection with the regional drainage is planned for 2020. Syncrude (2006) indicates in the mine closure plan for their Mildred Lake leases that BML will play an important water quality role by acting as a bioremediation and sediment trap for the rest of the lease as well as attenuating peak flows.

A major monitoring program is in place for BML, with much of the current research focus on the geotechnical aspects of MFT and process water chemistry, however once the MFT deposit is water capped, research efforts will shift to biological monitoring. Syncrude (2006) indicates that more monitoring is required to determine the long-term performance of the littoral zones and potential maintenance issues for closure, such as slumping. A second pit lake is planned at Syncrude's North Mine on a deposit of soft tailings at the completion of mining on the Mildred Lake leases.

Pros

- Cost-effective method to reclaim soft tailings (MFT, TT).
- Eliminates need for heavy equipment and reclamation material.
- Potential for sustainable ecosystem capable of supporting aquatic organisms.
- Creates central features of the reclaimed landscape for passive bioremediation, sediment traps, and attenuation of peak flows.
- Polishing of water prior to release in receiving water bodies.
- Geological containment for fluid tailings where stored below original ground.

Cons

- Regulatory shift towards creating a solid trafficable dry landscape.
- Concern over long-term sustainability and certification suitability.

- No surface water quality standards for discharging to receiving bodies such as the Athabasca River.
- Potential for groundwater contamination.
- Freshwater use.
- Methane evolution has been noted in some tailings ponds.
- Water management in general continues to be a challenge for extraction and tailings.

Knowledge Gaps

- Modeling to provide optimal regional design guidelines (such as optimal water cap thickness to avoid stratification of the underlying tailings deposit).
- Treatment for the intermediate layer between the MFT and the top recycled layer.
- Bioaccumulation and bio-concentration of toxic constituents (naphthenic acids, salts, ammonia).
- The role of microbes for biodegradation of naphthenic acids.
- Littoral zone development.
- Research into the processes responsible for labile and refractory naphthenic acids degradation.
- Technologies to reduce freshwater use and recycling.
- Defining water quality objectives within the range of natural variability in the region.
- Developing regional standards for eventual discharge release of treated process-affected water.
- Fish survival, reproduction and tainting.

Stage of Technology

- Applied research & demonstration.

4 RECLAMATION TECHNOLOGY ANALYSIS

4.1 Discussion

Current reclamation practices have evolved towards the development of self-sustaining ecosystems equivalent to pre-disturbance conditions. This represents a significant shift from early reclamation practices that focused on the use of grass and legumes to obtain erosion control objectives on tailings dykes and overburden storage dumps, towards a more holistic approach to landform design that considers all components of the ecosystem including geotechnical, surface water, groundwater, soils, vegetation and fish and wildlife (McKenna 2009), in addition to a greater focus on "ecosystem functioning" (Reclamation Criteria Advisory Group 2008). The use of natural analogues is an important design tool for achieving ecosystems with similar form and function. Understanding ecosystem processes and quantifying the range of variability observed in natural systems will be important research programs for designing and constructing wetlands and lakes in the reclaimed landscape.

Soil research has indicated that peat and overburden are ideal for tailings sand deposits, with alternative amendments such as overburden, tailings waste and sewage waste proving ineffective. The use of LFH, the organic layer on the forest floor, has proven to be effective technology for providing seed and propagule sources, and relatively efficient operationally.

Qualizza (2000) identified broad areas of long term soil covers research including understanding rooting zone development, soil salinization at the toes and flats of landforms, soil cover designs and evolution, channelization/gullying of fine tailings landforms, and assessment of capability for tailings sand and CT based landscapes.

4.2 Reclamation Technology Gaps

Historic areas of reclamation research have included the use of soil materials including peat:mineral mixes and overburden subsoil to overcome the limitations of tailings sand and improve plant growth and establishment.

Specific technology gaps for each technology are presented in Appendix 4. General areas of research are provided below (some of which are identified in Naeth and Wilkinson 2004):

- Soil nutrient cycling.
- Alternative soil amendments.
- Direct revegetation of CT deposits.
- Wetland design (fen/bogs) and construction.
- Shrub and wetland species propagation (especially salinity tolerance).
- Alternative seed sources (e.g., LFH).
- Freshwater use and treatment.
- Soil development and processes (along a catena).
- Operational techniques for soft tailings reclamation (landform grading, access).
- End Pit Lake development and monitoring.
- Terrain unit modelling for anthropogenic landforms (and GIS-based assessment tools).
- Indicators of reclamation success.

5 CONCLUSIONS AND RECOMMENDATIONS

An assessment of available literature indicates the following:

- Upland reclamation research is a mature technology; mines have largely advanced to a monitoring phase of commercial reclamation and are applying techniques to reclamation of soft tailings deposits, including wetland areas.
- An impressive amount of research on reclamation of soft deposits is widely available.
- Much of this research has been completed by university and government researchers and environmental consultants working closely with industry scientists and engineers.
- Several instrumented watersheds have been established as part of interdisciplinary studies to assess the following general questions related to the water and salt balance of reclaimed landscapes including:
    - Water balance: Where does the water go and under what processes?
    - Salt balance: Where does the salt go?
    - Plant and ecological response: How do plants (and to an extent wildlife) develop on reclaimed landscapes over time?
- Considerable technology transfer between researchers, designers, and operators is on-going, much of this facilitated by high-level CEMA documents such as:
    - Land Capability Classification System manual (CEMA 2007a).
    - Wetland manual (CEMA 2007b).
    - Vegetation manual (CEMA 2009, OSVRC 1998, OSSVWG 2002).
    - End pit lake manual (Clearwater Consultants 2007).
    - Landscape design manual (Millennium EMS Solutions Ltd. 2010).
- Wetland design is an active area of research and includes the construction of commercial demonstrations for pit lakes and wetlands on soft tailings.
- These commercial demonstrations provide many opportunities for research including:
    - A better understanding of the interactions between water, salt, soil cover designs and vegetation on soft tailings.
    - Design methods for lakes, channels and wetlands, especially related to hummock and watershed configurations to maintain sustainable water and salt balances.
    - Operational techniques for placement of wetland reclamation in soft areas.

    - Revegetation of fen/bog wetlands including plant species selection, propagation, planting technology, irrigation / flooding, fertilizing, monitoring for response to salinity and moisture gradients.
    - Design and construction for supporting traditional land use remains an area to be explored on wetlands.
    - Understanding how the water balance is responding to different capping thicknesses, substrates, watershed topography controls and vegetation prescriptions.
- Reclamation monitoring, including timeframes and indicators of success (CEMA 2010), is considered an important area for research because ecological processes such as carbon storage in reclaimed peatlands occur over large time scales.
- A process-based approach to research is recommended to understand ecosystem dynamics, including nutrient cycling, soil moisture dynamics and plant community succession on reclaimed fine tailings sites.

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APPENDIX 1: Glossary of Terms and Acronyms in this Report

Terms

Bog

A class of peat-accumulating wetland that is described as having a high water table that is usually at or above the surface and maintained from either groundwater discharge (acidic) or precipitation (termed: ombrotrophic bog). Vegetation consists dominantly of mosses (Sphagna), with some shrub cover and, at times, a sparse tree layer.

CNRL

Canadian Natural Resources Limited

Coarse-grained

With reference to soil, the texture exhibited by sands, loamy sands, and sandy loams but not including very fine sandy loam.

Coke

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

Composite/Consolidated Tailings (CT)

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

Consolidation

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

Dedicated Disposal Area (DDA)

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

Ecosite

(1) Originally referred to as a “land type”, an ecosite is a subdivision of an eco-section that consists of an area of land with a particular parent material, having a homogeneous combination of soils and vegetation. A Canadian ecological land classification (ELC) system mapping unit, usually mapped at a scale of 1:50 000 to 1:10 000.

(2) In Alberta, ecosite is defined as an area with a unique recurring combination of vegetation, soil, landform, and other environmental components.

Ecosite Phase

A subdivision of an ecosite based on the dominant tree species in the canopy.

Edaphic

Soil characteristics such as water content, acidity, aeration and nutrient availability which influence living organisms, rather than climatic factors.

Evapotranspiration

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

Equivalent land capability (regulatory definition)

The ability of the land to support various land uses after reclamation is similar to the ability that existed prior to any activity being conducted on the land, but the ability to support individual land uses will not necessarily be equal after reclamation.

Fen

A class of peat-accumulating wetland that is described as having a high water table that is usually at or above the surface; waters are mainly nutrient-rich and minerotrophic from mineral soils, but nutrients can be highly variable across the class; dominant materials are sedge and/or brown moss peat of variable thickness associated soils are Mesisols, Humisols, and Organic Cryosols; vegetation consists dominantly of sedges, grasses, reeds, and brown mosses, with some shrub cover and, at times, a sparse tree layer.

Fines Content

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

Fine-grained

With reference to soil, the texture exhibited by silt and clay a soil containing large quantities of fine fractions.

Hydroperiod

The period of time that a wetland is covered with water. This is based only on the presence of surface water and not its depth.

LFH

A thin organic layer on the forest floor consisting of litter (L), fibric (F) and humic (H) material and containing many viable seeds and propagules.

Maintenance-free

Reclaimed land that is sustainable without human intervention. It is recognized that natural erosion processes continually affect reclaimed landscapes.

Naphthenic Acids

A diverse family of saturated, polycyclic and acyclic carboxylic acids that occur naturally in petroleum deposits; the processing of bitumen in oil sands mining releases this family of chemicals to the soluble fraction of processed waste materials, and they may become concentrated in process-affected water found on reclaimed landscapes; prior to microbial break-down, some types of naphthenic acids are highly toxic to aquatic organisms.

Oil Sands

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

Overburden

The material below the cover soil layer and above the bituminous sand that may be used as a sub soil for reclamation.

Peat:mineral mix

Coarsely mixed peat and mineral materials salvaged during the stripping process in which peat is over-stripped to a maximum depth of 3 m and includes 25% to 50% by volume of mineral materials.

Pit Lake

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

Process-affected Water

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

Reclamation

The process which disturbed lands are returned to a beneficial land use.

Salinity

The concentration of salts dissolved in water; for the purpose of this document, electrical conductivity (EC, expressed as dS/m) is used as a surrogate for salinity.

Seepage

The flow of a fluid through soil pores.

Shell

Shell Canada Ltd.

Solids Content

Percentage of mass of solids to total mass of tailings.

Suncor

Suncor Energy Inc.

Syncrude

Syncrude Canada Ltd.

Tailings

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

Tailings Ponds

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

Acronyms

AENV	Alberta Environment
AOSR	Athabasca Oil Sands Region
ASRD	Alberta Sustainable Resource Development
BGC	BGC Engineering Inc.
CEMA	Cumulative Environmental Management Association
CT	Consolidate/Composite Tailings
DDA	Dedicated Disposal Area
EPEA	*Environmental Protection and Enhancement Act*
EPL	End Pit Lake
ERCB	Energy Resources Conservation Board
FT	Fine Tailings
FTFC	Fine Tailings Fundamentals Consortium
GCL	Geosynthetic Clay Liner
LCCS	Land Capability Classification System
LFH	Litter, Fibric, Humic
MFT	Mature Fine Tailings
MLSB	Mildred Lake Settling Basin

NA	Naphthenic Acid
OSRIN	Oil Sands Research and Information Network
OSVRC	Oil Sands Vegetation Reclamation Committee
PL	Pit Lake
TSM	Total Soil Moisture
TT	Thickened Tailings

APPENDIX 2: List of References Reviewed

Primary Author	Year	Title	Source
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Alberta Environment	2000	*Environmental Protection and Enhancement Act*	
Allen, E	2008	Process water treatment in Canada's oil sands industry: I. Target pollutants and treatment objectives.	Journal of Environmental Engineering and Science 7(2): 123
American Petroleum Institute	2003	Test plan for reclaimed substances: Streams containing naphthenic acids, phenolics, disulfides, acids or caustics	Submitted to the US EPA
Amon, J.P. et al.	2005	Construction of fens with and without hydric soils	Ecological Engineering 24: 341-357
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APPENDIX 3: Summary of Reclamation Technologies

Tailings Treatment Technology		Reclamation Comments		
		Stabilization /Capping Summary	Pros	Cons
	Filtered whole tailings	• Deposit may be trafficable to specialized equipment and suitable for hydraulic sand capping or reclamation • Relatively easy to reclaim using standard reclamation equipment and techniques	• Requires a smaller footprint for storage and no dam for retention • Recover large amount of process water • Filtration produces "dry tailings" for stacking requiring no dam for retention • Ease of progressive reclamation and closure of the facility, amenable to concurrent reclamation • Low long-term potential environmental impacts • No long-term consolidation settlements	• The process is costly due to the large amount of coagulant used and the high capital and operating costs for filtration equipment • Requires surface water management particularly for concentrated runoff • Water quality may be affected by flocculants (if used)
	Cross-flow filtration of whole tailings	• Stabilization techniques for technology represents a research gap		
	Filtered coarse tailings	• Stackable tailings. Easy to reclaim using standard reclamation equipment and techniques	• Results in a useful construction material with lower ionic contents	• Need to remove the fine fraction using a hydrocyclone or other methods • Compaction or special handling procedures required for deposits • High transport and deposition costs
	Filter thickened fines tailings	• Resulted tailings may still be soft and stabilization options will depend of the efficiency of the filtration	• Addresses legacy MFT	• Soft deposit, low trafficability
	Centrifuge fine tailings	• Water cap, hydraulic sand cap or reclamation material placement • Deposit may be trafficable to specialized equipment and suitable for hydraulic sand capping or reclamation	• Requires relatively small area • Recover large amount of process water • Addresses legacy MFT	• High upfront capital and operating costs makes scaling up operations challenging
	Thermal dry MFT	• Dry and stackable tailings. Easy to reclaim using standard reclamation equipment and techniques	• Thermal MFT drying eliminates water and diminishes the volume of the MFT by a factor of 4 to 5 • It lowers the transportation cost and facilitates storage • Rapid removal of moisture in MFT	• Thermal drying is noted for its high-energy demand
	Electrical treatment	• Stabilization techniques for technology represents a research gap		
	Blast densification	• Water or hydraulic sand capping	• Eliminate the potential for liquefaction	• Soft deposit, low trafficability
	Wick drains	• Allow rapid densification however the deposit may still require an application of geogrid to improve surface trafficability	• Can reduce settlement times from years to months • Potential to use with other technologies to accelerate consolidation	• Wick drains may not retain their shape and integrity over time due to large settlement • Difficulty getting equipment onto the soft deposit • Costly due to close spacing of wick drains
	Surcharge loading	• Coke cap can be placed on top of the MFT by sub-aqueous discharge	• Accelerate dewatering process • Can be used with wick drains to accelerate consolidation • Allows for trafficability of the deposit	• Difficult to place cap on top of MFT • Stability issues during cap placement (mud wave)
	CT under MFT	• Water or hydraulic sand capping	• Improve quality of CT release water	• Does not improve solids (MFT and CT) densification rates • Soft deposit, low trafficability
	Increase tailings density	• Stabilization techniques for technology represents a research gap		
Natural Processes	Sedimentation/self-weight consolidation	• Water or hydraulic sand capping	• The internal surcharge of coarse solids will accelerate the rate of dewatering of the contained fines	• Soft deposit, low trafficability • Equipment access may be an issue due to cyclic mobility (liquefaction) during trafficking • Takes significant time to consolidate and reclaim
Natural Processes	MFT evaporation/drying	• Surface is trafficable with modest equipment and suitable for hydraulic sand capping and terrestrial reclamation	• Formation of crust with adequate strength to support equipment • Post-reclamation settlement is expected to be small • Development of natural cracks as shrinkage occurs provides drainage channels for horizontal movement of water and additional surface area for evaporation • Potential to spray MFT in layers (2 to 3 cm) onto tailings beaches to control blowing sand	• Requires surface water management • Large areas are required for treatment
Natural Processes	Accelerate dewatering	• Surface is trafficable with modest equipment • Soft material that can be suitably capped and reclaimed	• Can reduce MFT volume by up to 50% after three to five years • Formation of cracks accelerate dewatering process	• Requires additional disturbance footprint

Tailings Treatment Technology		Reclamation Comments: Stabilization /Capping Summary	Reclamation Comments: Pros	Reclamation Comments: Cons
	Freeze/thaw	• Material remains saturated - only suitable for hydraulic sand capping or reclamation using specialized equipment	• Results in materials that are stronger than TT • Process significantly reduces the volume of fine tailings • Freeze-thaw tailings found to have potential as a reclamation material	• Requires large footprint
	Biological/plant (evapotranspiration) dewatering	• CT deposit can be planted with appropriate grasses, shrubs or trees when deposit is trafficable	• Suitable plant species can grow in the tailings, removing water by transpiration through the leaves during the growing season • Root development increases bearing capacity at the tailings surface facilitating access of low pressure equipment for reclamation	• High salinity of tailings can inhibit healthy growth • Limited by root depth • Placement of fertilizer, seedlings/seeds and other amendments onto large deposits is not well developed • Depth of dewatering in limited by root depth • Concern regarding use of non-native and potentially invasive species
Chemical/Biological Amendment	Thickening process	• Water or hydraulic sand capping	• Recover process water and reduced groundwater impacts • Potential of accelerated land reclamation from a more stable deposit	• Long-term consolidation settlement • Large footprint
Chemical/Biological Amendment	In-line thickened tailings (ILTT) technology	• Water or hydraulic sand capping	• Improved quality of the recycle water	• Relatively harder deposit compared to MFT however not trafficable if surface drying is not allowed or only trafficable with specialized equipment • Potential adverse impacts on water quality due to the addition of coagulants and flocculants • Requires increased operational control • High operational cost
Chemical/Biological Amendment	Whole tailings coagulation	• Water or hydraulic sand capping	• Deposit may be trafficable using standard reclamation equipment	• High operational cost • Potential adverse impacts on water quality due to the addition of coagulants and flocculants
Chemical/Biological Amendment	Whole tailings flocculation	• Water or hydraulic sand capping	• Deposit may be trafficable using standard reclamation equipment • Recovers large amount of process water • Sedimentation and initial consolidation commence almost immediately after deposition and is complete within a short period of several days to a few weeks	• Unpredictable performance due to tailings variability • Requires enhanced operational control/care • Use of chemical reagents may generate possible detrimental effects on recycle water quality • High operational cost
Chemical/Biological Amendment	In-situ biological treatment	• Water or hydraulic sand capping	• Low cost	• Soft deposit, low trafficability • Process is difficult to control in a large scale • Lack of understanding of microbes present in MFT
Chemical/Biological Amendment	In-situ chemical treatment	• Water or hydraulic sand capping	• If stabilization is successful, may consider geogrid and sand cap to improve trafficability	• Soft deposit, low trafficability
Chemical/Biological Amendment	Reduce dispersion of fines in process	• Water or hydraulic sand capping	• Allows hydraulic sand capping soon after deposition and can subsequently be reclaimed to support terrestrial land uses	• Soft deposit, low trafficability • Does not appear to enhance long-term consolidation rates • Total volume of soft material increased substantially
Mixtures/Co-disposal	Composite/consolidated (CT) tailings	• Water capped • Hydraulic sand capped (>1.6 m ideal) • Deposit may be trafficable using standard reclamation equipment (issues with liquefaction)	• Consolidates over a short time (several decades) to form a solid landscape for reclamation • Wetland and riparian plant communities can develop on CT materials in areas affected by CT water • Potential to managing salt effects from CT release water through surface topography design, sand capping thicknesses, surface water drainage and choice of reclamation species • Underdrains can help to prevent the influx of process-affected water while vegetation establishes	• Requires large quantities of tailings sand • Susceptible to liquefaction when placing reclamation material • Potentially causes H_2S emissions by anaerobic reduction of SO_4^{2-} with the residual bitumen in the tailings • Potential toxicity effects of CT and CT release water on plants when solution exceeds 4 dS/m (NaCl more detrimental than Na_2SO_4) • Sodium, chloride and boron accumulation in needles/leaves of planted trees observed in systems where CT is present in the root zone, resulting in mortality
Mixtures/Co-disposal	MFT spiked tailings	• Water or hydraulic sand capping	• Addresses legacy MFT • Practical and cost effective	• Soft deposit, low trafficability • Trafficability of spiked beaches is marginal • Additional fines in the deposits would also affect consolidation
Mixtures/Co-disposal	Mixing MFT with Clearwater overburden	• Deposit may be trafficable using standard reclamation equipment (issues with liquefaction)	• Clearwater (Kc) is abundant in overburden in the mineable oil sands area • Strength and rapid stabilisation of the co-disposal waste allows earlier trafficability	• The resulting mix would not be pumpable

Tailings Treatment Technology		Reclamation Comments		
		Stabilization /Capping Summary	Pros	Cons
			• Co-disposal storage does not require retention embankments	
	Mixing MFT with reclamation material	• Deposit may be trafficable using standard reclamation equipment (issues with liquefaction)	• Strength and rapid stabilisation of the co-disposal waste allows early access onto the tailings for reclamation • Addresses legacy MFT • Surface material will be ready for reclamation • Reduces need for secondary reclamation material	• Addition of MFT to reclamation soils found to have negative effect on plant growth in the short term (magnitude of toxicity decreased over time) • Limited availability of reclamation material • Expensive
	Mixing MFT with coke	• Deposit may be trafficable using standard reclamation equipment (issues with liquefaction)	• Potential to cap soft tailings with coke • Potential to use coke as an underdrain to accelerate soft tailings consolidation • Co-disposal storage does not require retention embankments	• Coke, a source of energy, can be lost in a deposit or difficult to obtain if later required • Benefits are unclear
	Mixing thickened tailings with sand	• Water or hydraulic sand capping	• Co-disposal storage does not require retention embankments • Deposit may be trafficable using standard reclamation equipment • Strength and rapid stabilisation of the co-disposal waste allows early access onto the tailings for reclamation	• Potential environmental issues because of the presence of sodic clays and bituminous residues in oil sands tailings
Permanent Storage	MFT water capped lake	• Water cap • MFT lacks sufficient strength to form a trafficable surface	• Low cost • Reduction of concentration of chemicals and toxic compounds through natural microbial processes • Self-sustaining aquatic ecosystem • Potential for dilution of process-affected water and increased residence times for achieving water quality objectives	• Consolidates over long time periods (50 to 100 years) • Some gas generation • Possible mixing between MFT and overlying water cap • Many uncertainties regarding function and success including water quality and toxicity, sustainability, productivity and liability • Regulators have not yet approved permanent storage of MFT under a water cap. Instead they have advocated for a solid trafficable landscape
	End Pit Lakes/ Saline wetlands	• Water cap	• Potential for saline tolerant vegetation to establish in constructed wetlands	• Many uncertainties regarding function and success including water quality and toxicity, sustainability, productivity and liability
	Store MFT in underground cavern	• No surface disturbance or surface tailings storage area required	• Tailings are generally mixed on the surface with a binder to help minimize groundwater contamination • High costs, particularly if binders are used • Requires suitable location and development of caverns	• Risks of liquefaction of the tailings if saturation levels are high • Potential for groundwater contamination

APPENDIX 4: Technology Gaps

Reclamation Treatment Technology		Technology Gaps
Stabilization	MFT Water Capped Lake	Refer to Pit Lakes
	Hydraulic Sand Capping	• Optimization of sand cap thickness to prevent salinization of rooting zone, adequate flushing of salts and to allow trafficability • Availability of tailings sand is an operational concern to be considered
	Hydraulic Coke Capping	• Incorporation of other waste streams (e.g., sulphur, coke, gypsum) • Floating coke covers over a geosynthetic clay liners (GCL) over soft tailings requires further research
	Mechanical Tailings Sand Placement	• Techniques to improve the formation of a crust (e.g., freeze/thaw) to improve trafficability and cost-effectiveness of technology
Soil Cover	Peat and Overburden	• Hydraulic placement of reclamation material • Optimal cover thickness for wetland establishment and decomposition of peat under saturated conditions • Understanding long-term soil moisture and nutrient dynamics in soft tailings caps • Understanding and predicting salt movement from tailings into reclamation materials • Additional research required on the optimal placement depth of peat material for wetland development
	LFH Transplants	• Upland forest research challenged to create A/B ecosites; potential use of LFH to create A/B ecosites on a commercial scale • Investigation into which species (shrubs, herbs) are recruited from LFH applications conducted at a commercial scale for upland and wetland revegetation • Uncertainty around the long-term vegetation community benefits of LFH vs. traditional peat:mineral mixes
Topography	Watershed Design	• Watershed reconstruction to control water balance and fluxes of process affected water • Determining optimum topographic configurations and ratios (uplands, wetlands) to manage surface/ groundwater interactions • Developing methods to reduce tailings sand containment footprint • Landform design techniques for establishing self-sustaining, self-repairing drainage system for natural appearance and landform integration with creeks, wetlands and lakes
	Topographic Controls (hummocks and swales)	• Further empirical data and modeling required for long-term flushing rates from hummocks constructed using different tailings materials and configurations; texture of the hummocks is hypothesized to be a critical factor in the ability of the watershed to supply enough water to sustain the reclaimed landscape long-term • Research into the optimal hummock design (shape, slope, aspect, orientation) for flushing salts and preventing salinization of the rooting zone • Planting schemes for hummocks (uplands, wetlands and transition zone between zones) • Flushing rates as a function of hummock height • Understanding hydrological processes at transition zones between upland hummocks and wetlands
	Differential Settlement	• Post-reclamation settlement may play a role in increasing micro-topographic diversity in the post-reclamation landscape, although this mechanism is yet to be studied • Spatial variability in settlement as a result of applying multiple tailings technologies • Further development of models to predict areas of settlement
lin ity Co nt	Seepage Controls	• Quality of leached water from various waste materials and reconstructed topography

	Reclamation Treatment Technology	Technology Gaps
		• Characterizing process-affected seepage waters from tailings sand tailings sand, CT deposits and newer tailings management technology deposits (e.g., Suncor's Tailings Reduction Operations – Suncor 2009) • Quantifying the amount of process-affected water not recovered by seepage controls including monitoring of groundwater flow • Research needed in the area of salinity controls to better quantify the long term water quality of seepage water discharged from newly reclaimed tailings landforms • Suitability and availability of native plant materials for use in salinity-affected wetlands • On a regional scale, a better understanding of the environmental impacts of process-affected seepage water discharge on receiving water bodies such as the Athabasca River
	Underdrains	• Technical documentation of operational techniques used to install and monitor underdrains • Understanding the "zone of influence" of each underdrain for seepage control • Optimizing the number of underdrains per hectare to effectively control seepage on a deposit • Examining alternative materials as underdrains (such as gravel)
Revegetation	Plant Selection	• Revegetation of overburden, tailings sand and consolidated tailings with a soil cap is well established, but less well known is the establishment of sustainable ecosystems with natural processes • Native shrub propagation and planting at a commercial scale • Salinity tolerances of wetland plants • Selection, availability and planting of wetland plants at a commercial scale • Role of mycorrhizal associations for plant suitability on CT
	Hydro-seeding	• Identification of soil amended slurries that can flow through a pipe • Selection of plant species that can germinate in a given slurry
	Fertilization	• Further research required to optimize fertilizer application rates to increase germination of native species • Potential to "push" plant community towards a specific target ecosite using fertilizers, but this is poorly understood • Alberta Sustainable Resource Development is concerned about the sustainability of vegetation and communities following withdrawal of fertilizer applications

End Land Uses	Wetlands	• Documented case histories from the region with detailed empirical data on fundamentals for wetland design including:
		    ○ percolation rates for upland areas
		    ○ actual evapotranspiration rates
		    ○ climate histories (as input to models)
		    ○ substrate saturated and unsaturated permeabilities and soil-water characteristic curves
		    ○ vegetation planting schemes
		    ○ designs for influent and outflow structures for oil sands areas
		    ○ typical reclamation equipment and unit costs
		    ○ topographic controls (wetland:upland ratio), watershed area
		• Strategies for growing and planting salt tolerant vegetation at an operational level
		• Better understanding of how wetlands will transition from moderate to low salinity over decades and centuries as soft tailings consolidate
		• Geosynthetic clay liners (GCLs) have been used in wetland design, but are not required for design. The longevity of GCLs for perched wetlands is a design issue. Additional research is required to protect deterioration from freeze-thaw and chemistry effects for permanent reclamation.

Reclamation Treatment Technology		Technology Gaps
		• Operational placement techniques for salvaging and transplanting live peat • Techniques for returning peat-accumulating plant species and the impacts of salt on establishment on a site. Still uncertain whether vegetation in the oil sands region can be effective in removing a significant portion of salts from solution by plant uptake • Hydrological (and hydrogeological) processes that will sustain wetlands over time • Potential of wetlands as carbon sinks; understanding the carbon balance • Changes in microbial community structure over time • Potential indicators of reclamation success and time frame for monitoring • Refer to a recent scoping study conducted by CEMA (2010) for additional knowledge gaps, including interviews with key academic wetland researchers
	Upland Forests	• Re-vegetation of soil caps on mine wastes (overburden, tailings sand, CT) are understood – less understood is target ecosite and reconstruction and establishment of boreal forest ecosites • Maximum rooting zone depths for individual plant species • Continued emphasis on understanding mycorrhizal development to enhance plant establishment • Recovery process for ecosystems from disturbances (e.g., fire, drought, erosion, beaver activity, etc.) is not well understood • Process-orientated physically based models for vegetation community development over time • Modelling required to understand the potential impacts of climate change on vegetation, hydrology and soil moisture using a range of greenhouse gas emission scenarios
	Pit Lake	• Modeling to provide optimal regional design guidelines (such as optimal water cap thickness to avoid stratification of the underlying tailings deposit) • Treatment for the intermediate layer between the MFT and the top recycled layer • Bioaccumulation and bio-concentration of toxic constituents (naphthenic acids, salts, ammonia) • The role of microbes for biodegradation of naphthenic acids • Littoral zone development • Research into the processes responsible for labile and refractory naphthenic acids degradation • Technologies to reduce freshwater use and recycling • Defining water quality objectives within the range of natural variability in the region • Developing regional standards for eventual discharge release of treated process-affected water • Fish survival, reproduction and tainting